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Photo 1. Yosemite Valley from the air. Sentinel Peak in the right foreground. Tenaya Creek, on the north side of Half Dome, and Tenaya Creek meet in the center of the photo. *Photo by Sarah Ann Davis.*

ETROGRAPHY OF SIX GRANITIC INTRUSIVE UNITS N THE YOSEMITE VALLEY AREA, CALIFORNIA*

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ABSTRACT

etrographic examination of specimens from six gra- trusive units in the Yosemite Valley area suggests a do reclassify four of these units.[1] The classification by ks was made while mapping these intrusive rocks dur- e 1920's. Although Calkins' megascopic descriptions cellent and his contacts have stood the test of time, e modal data indicate that four of the igneous units u be lithologically reclassified and classification of ner two remain as proposed by Calkins:

Calkins' (1930) classification	Average modal classification
granite of Arch Rock	granodiorite
iorite of "The Gateway"	quartz diorite
itan Granite	granodiorite
ranite	quartz monzonite
l Granodiorite	granodiorite
ome Quartz Monzonite	quartz monzonite

l lithologic classification is based on the one used by lms, Turner, and Gilbert (1955).

m this quantitative examination, the average compo- l of the Sentinel Granodiorite is practically on the lary line between granodiorite and quartz diorite. alf Dome Quartz Monzonite was not sampled enough ermine a representative mean but the limited analyses an average composition near the granodiorite-quartz nite divide. Calkins' (1930) classification of these in- e bodies therefore, is correct in regard to the modal presented within the classification scheme used here.

uscript based on unpublished MS thesis, University of California, eley, 1958. Submitted for publication March 1965.
nal unit.

INTRODUCTION

Yosemite Valley lies on the western flank of the Sierra Nevada on the Merced River in Mariposa County. It is approximately 90 miles northeast from Merced, California, on State Route 140.

The intrusive bodies of Yosemite Valley were mapped by F. C. Calkins (1930, p. 121) and grouped in two intrusive series: the biotite granite series of the Yosemite Valley, and the Tuolumne intrusive series.

This grouping of intrusive units is not necessary for the purposes of this report and is not used here. The units, therefore, will be considered separately beginning with the oldest and ending with the youngest according to the intrusive sequence established by Calkins. The purpose of this report is to present the petrographic aspects and some data on the modal composition for six of these intrusive units. A reclassification of the rock type is suggested for four of these units originally named by Calkins.

Table 1. Comparative classification of major intrusive units in the Yosemite Valley.

Calkins' (1930) classification	Classification based on average modal composition
Biotite granite of Arch Rock	Granodiorite of Arch Rock[1]
Granodiorite of "The Gateway"	Quartz diorite of "The Gateway"[1]
El Capitan Granite	El Capitan Granodiorite
Taft Granite	Taft Quartz Monzonite
Sentinel Granodiorite	Sentinel Granodiorite
Half Dome Quartz Monzonite	Half Dome Quartz Monzonite

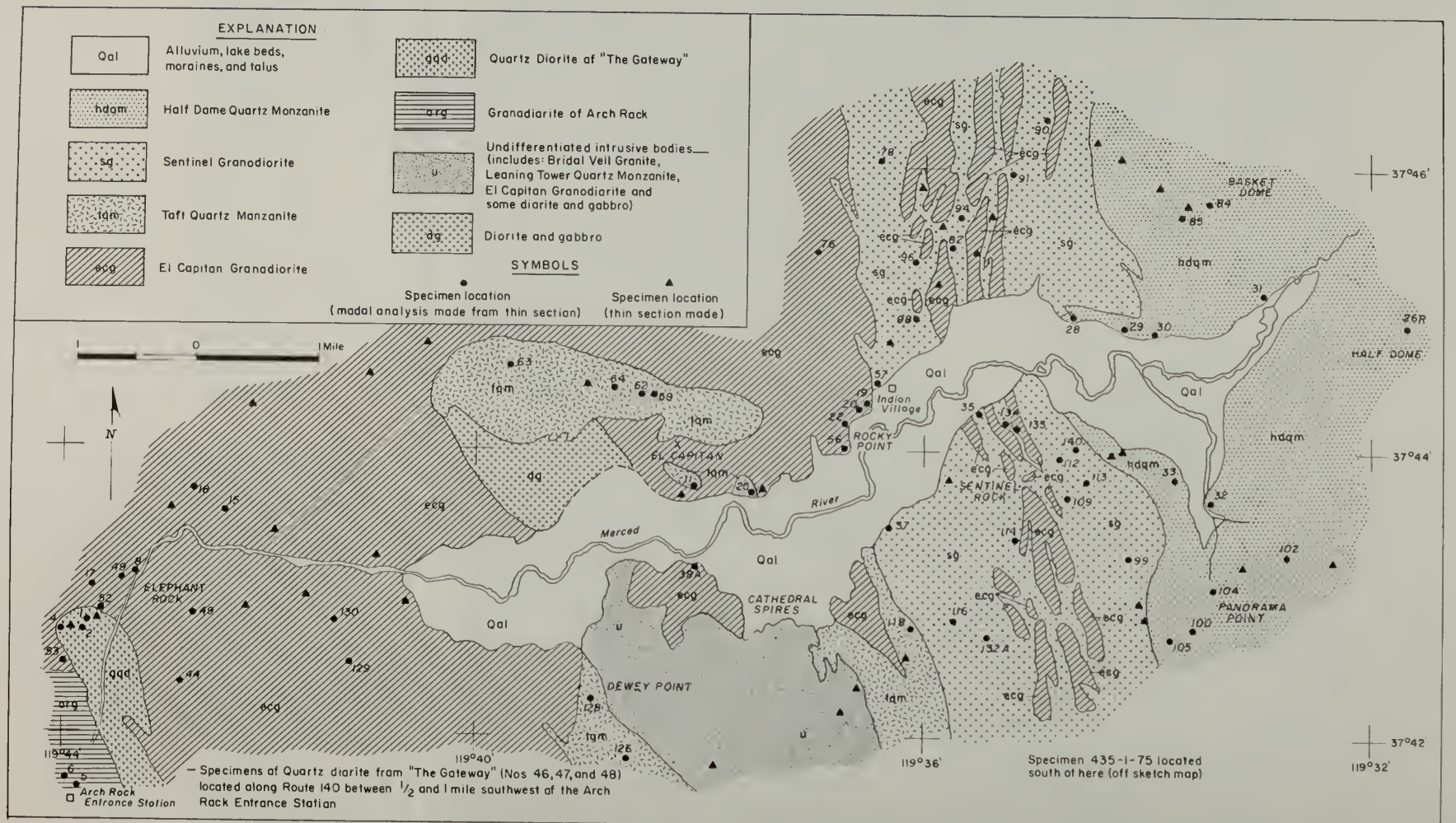


Figure 1. Generolized geologic mop of the Yosemite Volley oreo, Californio, showing somple locotions and approximote contoct of the gronitic intrusive bodies.

of Classification

n classification for acid igneous rocks used in p er is that used by Williams, Turner, and Gil- (955, pages 121, 93). All of the rock types con- a least 10 percent modal or normative quartz a separable by their ratio of alkali feldspar to o ase as follows:

Name	Ratio of volume of alkali feldspar to volume of total feldspar
z orite (tonalite)	<1:8
drite	1:8–1:3
z onzonite (adamellite)	1:3–2:3
e	>2:3

ough Williams (1955) qualified diorite as con- less than 1:3 alkali feldspar relative to the r of total feldspar in his classification table, e later qualifies this limit (page 107, 3rd para- n

'In the United States, however, most geolo- s adopt Lindgren's original definition of gran- orite, restricting the term to rocks in which hoclase makes up 13.3–33.3 percent (roughly m an eighth to a third) of the total feldspar. cording to this definition, diorites are rocks in ich less than an eighth of the feldspar is po- sic, and the silica percentage may be above or ow 66."

modal content of quartz in the plutons sampled ater than 20 percent, with the exception of the diorite of "The Gateway" in which it ranged n 9 and 25 percent.

how some of the percentage fluctuations that e attributed to sampling error, two different were cut from three different samples. Point- nalyses of the six sections are as follows:

ple ber	Quartz	Alkali feld- spar	Pla- gio- clase	Bio- tite	Horn- blende	Accessory minerals	
						Opaque	Non- opaque
-------	23.6	1.5	58.8	9.9	4.5	1.2	0.5
-------	25.6	4.8	58.7	6.6	2.4	0.9	1.0
9------	16.9	9.9	48.4	10.9	12.1	0.6	1.1
9------	15.3	10.7	52.7	13.0	5.2	1.3	1.2
-------	12.7	4.1	57.8	15.6	7.1	1.0	1.7
-------	15.5	4.2	62.2	14.3	0.9	1.4	1.5

comparison of modal values for two thin sec- om each of three different samples indicates a im variability between 3 and 4.5 percent, by , for quartz, alkali feldspar, plagioclase, and Hornblende, generally less abundant than the other constituents, shows a 7 percent variability in volume. This suggests that the result of random sectioning is not as significant in the major mineral constituents than it may prove to be in the case of hornblende, which is less abundant.

Methods of Study

Rock specimens were collected at random from valley walls and trails that rim Yosemite Valley and Merced Gorge; 109 thin sections were studied petrographically. The alkali feldspar was stained by a solution of sodium cobaltinitrite in order that rapid identification might be made in counting (Chayes, 1952). The anorthite content of plagioclase was determined by Michel-Levy's method of measuring the maximum extinction angle of albite twins in sections normal to the {010} crystal face (Rogers and Kerr, 1942, p. 241–2). Mineral proportion by volume was determined on 71 thin sections by the point-count method (Chayes, 1949). Modal values were based on 1400 to 1600 points covering most of a standard size thin section.

PETROGRAPHY

The petrographic aspects of these intrusive units are summarized in Table 2. The megascopic aspects are touched on very lightly since Calkins' field description of the intrusive bodies is quite complete. The distinguishing petrographic and modal data of the intrusions are compared in a section of this report following Table 2. Tables which present the modal analysis for each specimen examined are included in the appendix.

Granodiorite of Arch Rock

Prominent grid twinning shown by the microcline crystals is a distinctive microscopic feature of the granodiorite at Arch Rock. Other characteristics include the prevalence of euhedral sphene, and about 1 to 2 percent by volume of myrmekite. Olive brown biotite is the dominant mafic mineral and hornblende is essentially absent to rare. The composition of the two samples examined indicates a granodiorite type.

Quartz Diorite of "The Gateway"

The plagioclase grains in specimens examined from the quartz diorite unit at "The Gateway" (term used by Calkins (1930) apparently for the entrance to Yosemite Valley) exhibit a distinct oscillatory zoning. Also, the alkali feldspar which averages about 3 percent by volume occurs interstitially; the mafic minerals have a shredlike appearance under the microscope; and myrmekite is negligible. Biotite crystals (13.8 percent by volume) are about four times more abundant than hornblende crystals. Accessory minerals include zircon, sphene, apatite, and opaque grains and range between 2 and 3 percent, which is slightly more than in other plutons. With one exception, modal values of six point-count analyses are each of a quartz diorite composition.

Table 2. Petrographic data on granitic units of the Yosemite Valley area, California.

INTRUSIVE UNITS	GRAIN SIZE	MEGASCOPIC FEATURES	TEXTURE	DIAGNOSTIC MICROSCOPIC FEATUR
Granodiorite of Arch Rock	Range ½–4½ mm.	Light gray, medium-grained rock, only slightly weathered on exposed surface due to its dense nature.	Hypidiomorphic granular	Poikilitic microcline with excellent grid twinning and spar intergrowths, prominent bands of sericite within plagic euhedral sphene are characteristic. Plagioclase grains enclose cline are corroded and rimmed, in part, with myrmekite an ary" albite. Slides contain between 1 and 2 percent by myrmekite.
Quartz Diorite of "The Gateway"	Range ¼–3 mm, average ¾–2 mm (occasional plagioclase phenocryst up to 10 mm long).	Dark gray, medium- to fine-grained rock with abundant biotite and hornblende.	Hypidiomorphic granular	Distinctively zoned plagioclase crystals and interstitial alk are distinctive features. Also notable: a corroded, shred-like of the mafic minerals; poikilitic, anhedral quartz; and a amount of myrmekite. About 20 percent of the plagioclase antiperthitic.
El Capitan Granodiorite	Range ½–7 mm (occasional feldspar phenocrysts are at least 11 mm in diam.)	Light gray, medium to coarse-grained locally fine-grained near western contact. Extensively weathered with yellow-brown cast.	Hypidiomorphic granular —locally porphyritic. (a "vaguely" porphyritic variety is quite typical, according to Calkins, 1930)	The antiperthitic nature of plagioclase crystals, poikilitic alkali feldspar grains with strings of microperthite and p twinning are distinguishing traits. Anhedral, fractured q pronounced wavy extinction. Hornblende is essentially abs amounts locally near western contact). As alkali feldspar crease in size from 4 mm to 7 mm from west to east, the vo feldspar also tends to increase in the same direction.
Taft Quartz Monzonite	Range ¼–8 mm, average 1–3½ mm (quartz and microperthite crystals may reach 8 mm in diameter in central part of the intrusion).	Very light gray, medium-grained (resembles the El Capitan, but is finer grained and more uniform).	Variable-hypidiomorphic granular for the most part. Upland samples, north side of Valley are allotriomorphic with interstitial microgranular areas.	Abundant myrmekite is a characteristic feature of the T. largely in microgranular patches, also at the contact of plagi microperthite. Perthite occurs either as crudely aligned stri or en echelon pattern. Plagioclase shreds, having parallel o are enclosed in microperthite which exhibits a trace of "gho Averaging about 3 percent by volume, biotite is the only stituent observed.
Sentinel Granodiorite	Range ½–6 mm (occasional mafic phenocryst up to 14 mm long).	Medium-dark gray and medium-grained granular, but is variable in both color and texture.	Hypidiomorphic granular; much of the quartz and hornblende is anhedral in outline (locally porphyritic).	Western type: Characterized by poikilitic, distinctly zoned plagioclas poikilitic alkali feldspar with indefinite extinction, no grid and only a trace amount of myrmekite. Biotite and horn generally in clusters, and average about 10 percent and 5 p volume) respectively. Strain shadows and slight fracturing hedral quartz grains. Eastern type: Green hornblende, frequently ragged in outline, has c inclusions of quartz, plagioclase, biotite and accessory mi frequently surrounds a corroded clinopyroxene remnant. biotite (often with curved lamellae) and hornblende are more than in the western type. The K-feldspar is either interstitial corroded plagioclase crystals. Quartz has definite extinction to that above and in other plutons.
Half Dome Quartz Monzonite	Range <⅜–8 mm, average 2–5 mm (occasional mafic mineral up to 10 mm in length)	Light-gray, medium-grained rock. White and salmon mottling of the feldspars with interspersed euhedral biotite tablets and prisms of hornblende.	Hypidiomorphic granular (Many specimens have a distinct difference in grain size, e.g. average 2–5 mm to <⅜ mm.)	Alkali feldspar encloses all other mineral phases; the enclos clase is rimmed with secondary albite; quadrille structure of appears as irregular veins, along with crudely aligned strings perthite. Fractured quartz veined with albite, shows marke tory extinction. Common to about a third of the specimens is a distinct difference in grain size, from an average betwee mm to an interstitial groundmass less than ⅜ mm in diamet

El Capitan Granodiorite

The composition of El Capitan Granodiorite ranges from that of a tonalite to a quartz monzonite. The mean composition, however, is that of a granodiorite.

Exposed surfaces characteristically are stained yellow brown and extensively weathered. Microscopically, the diagnostic features of the pluton are: (1) antiperthitic plagioclase crystals; (2) extensively fractured quartz showing a pronounced undulating extinction; (3) ubiquitous allanite, and negligible hornblende.

The band of inclusions in the Sentinel Granodiorite are mapped as El Capitan Granite by Calkins. Texture and modes of the two specimens examined (Appendix C, part c) resemble the western part of El Capitan pluton. The four specimens between Rocky Point and Indian Village (north side of the valley, Appendix C, part b) present a slightly different mineralogy but are quantitatively similar to the main body. These four specimens differ from the typical El Capitan specimen in having euhedral sphene, about 3 percent hornblende, plagioclase that is not antiperthitic and lacking allanite (see map for location).

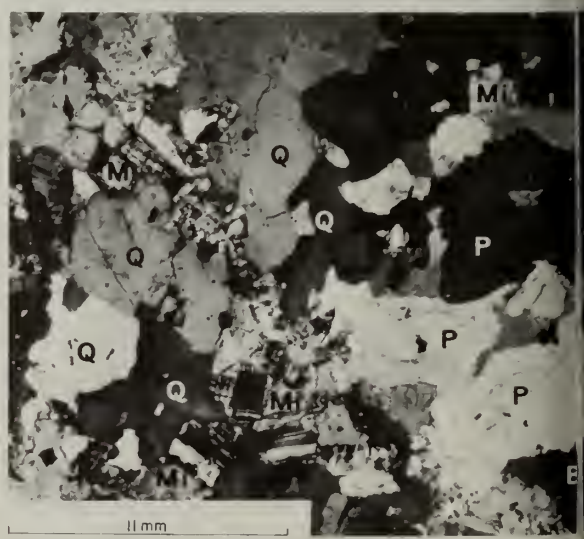


Photo 2. El Capitan Granodiorite. Photomicrograph shows th granular nature and patchy grid twinning of the potassium (microcline) that is common in the eastern half of the outcro Capitan Granodiorite. Note also the coarse-grained quartz (grain in the top center is more than 6 mm in size.

Table 2. Petrographic data on granitic units of the Yosemite Valley area, California.

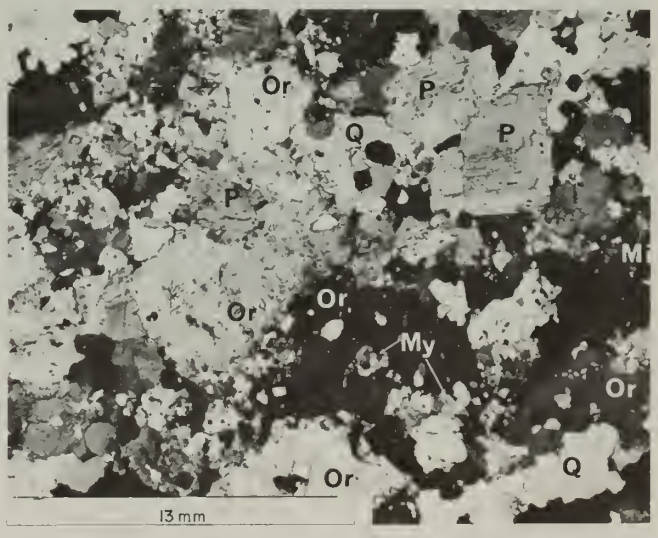
ACCESSORY MINERALS	ALTERATION FEATURES	PLAGIOCLASE COMPOSITION	Number of thin sections examined
(1–1.5%) phene dominates, also apatite, opaque n, and allanite.	Alteration is mainly confined to plagioclase grains and consists of a clay, sericite, epidote, and albite assemblage.	An_{17}–An_{28} Subhedral, zoned, and shows polysynthetic, simple, and complex twinning.	2
(2–3%) ne, apatite, and opaque grains. Irregular f sphene characteristically border grains d magnetite where enclosed in or in con-tite.	Insignificant sericite or other alteration products. Variable epidote (<0.5–>2.0) percent.	An_{22}–An_{38} Oscillatory zoned crystals with polysynthetic and complex twinning. (Ranges to An_{50} in one sample near contact.) Mottled centers occur in most of the plagioclase grains but with insignificant alteration.	8
(<1%) llanite between ¼ and ¾ mm in diameter. es, zircon, sphene, associated mainly with	Epidote associated with plagioclase and mafic minerals, and chlorite with biotite are common.	An_{20}–An_{34} Anhedral to subhedral, variable zoning, sutured contact with quartz. The percent anorthite range in plagioclase grains is well defined in determinations on more than 25 grains.	31
(0.1–0.5%) nt of accessory minerals: (including) zir-s, apatite and allanite.	Sericite, where counted, varies from a trace to 0.8 percent, associated with feldspar minerals. Insignificant chlorite and epidote with biotite.	An_{9}–An_{28} Anhedral grains up to 3 mm in size in which twinning and zoning are nondistinctive (antiperthite developed in some). Plagioclase grains in specimens from north side of valley, range between An_{9}–An_{18} in composition.	13
(0.5–2.5%) opaque minerals are most abundant, also e and zircon. Trace of hematite with mag-in four specimens.	Alteration is similar in both the western and eastern types. Plagioclase cores are generally altered to clay; epidote occurs with mafic minerals; and streaks of chlorite in biotite.	An_{24}–An_{47} Distinctly zoned; polysynthetic and complex twinning. A few plagioclase crystals in each slide were markedly sieved with inclusions; an occasional antiperthite patch occurred in less than 10 percent of the grains.	26
(<0.5–3%) erals comprise about 0.8 percent by vol-is next most abundant, with minor apa-and allanite.	Many plagioclase crystals are extensively mottled and altered in central part to clay, sericite, zoisite, and clinozoisite. Epidote occurs with either biotite or hornblende and streaky chlorite in biotite. (Alteration minerals are distinctive and more prevalent than in the Sentinel pluton.)	An_{22}–An_{45} Most of the anorthite determinations range between An_{28}–An_{40} as in the Sentinel pluton. Complex twinning with distinct zoning is common.	24

rtz Monzonite

nine specimens quantitatively studied from the uartz Monzonite fall within the compositional f a quartz monzonite. This is notable because rge intrusive masses in Yosemite Valley have range in composition.

scopically, the Taft Quartz Monzonite resem-anodiorite from El Capitan pluton, but is as coarse grained nor as brown in color on ed surfaces. Feldspar phenocrysts, which ap-some weathered surfaces of El Capitan Grano-are not apparent in the Taft intrusive body. xture is variable. Specimens from the north Yosemite Valley have an allotriomorphic tex-th interstitial areas of micrograniular myrme-l felsic minerals, whereas micrograniular areas prevalent in specimens from the south side valley where 3½ mm is the upper limit of ze.

prevalence of myrmekite is a characteristic fea-the Taft pluton. Poikilitic microperthite in-anhedral plagioclase that is either fringed with ry albite, or substantially replaced by myrme-sewhere, plagioclase shreds, that have parallel



Phata 3. Taft Quartz Monzanite fram north side af the Valley. Photomicrograph af Taft Quartz Manzanite showing the variable grain size an the north side af Yosemite Valley. Micragranulor patches af quartz (Q) ond myrmekite (My) occur in o fine ta medium-grained matrix af anhedral quartz and perthitic patassium feldspar (Or). Plagiaclase grains as shown in upper right accur sporadically.

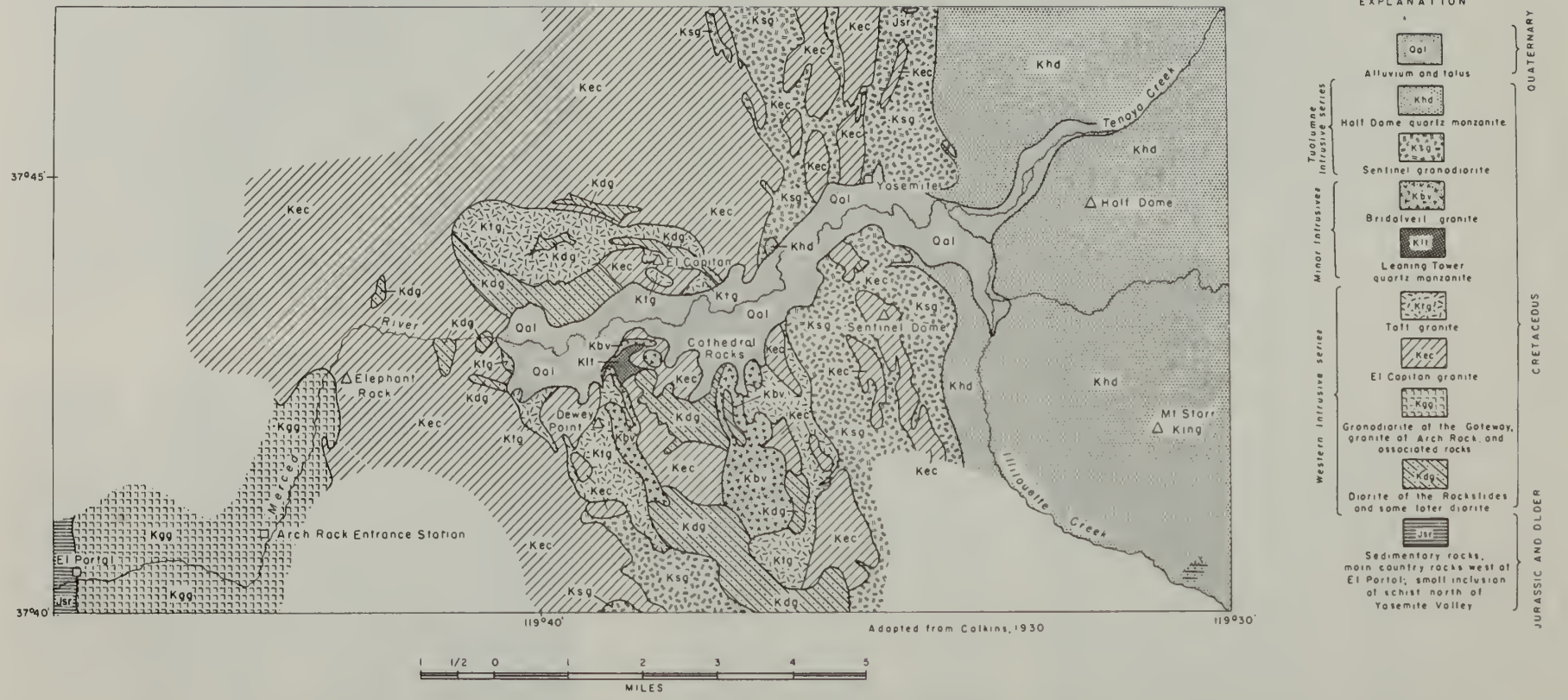


Figure 2. Sketch map of the Yosemite Valley area.

Table 3. Mean and range of modes of specimens from intrusive bodies of the Yosemite Valley area.

(Volume percent)

LUTON	Quartz		K-Feldspar		Plagioclase		Biotite		Hornblende		[1]Accessory minerals	
	Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range	Opaque	Non-opaque
Granodiorite of rch Rock	21.2	19.4–23.1	18.0	17.8–18.2	52.5	49.9–55.2	6.9	6.0–7.7			0.6	0.8
Quartz diorite of "Gateway"	18.4	9.2–24.9	3.1	0.5–10.0	58.4	53.6–66.4	13.8	11.6–16.2	3.7	2.7–6.0	1.2	1.4
Capitan Granodiorite	30.4	23.9–43.5	15.6	3.9–23.4	45.2	29.5–62.4	7.0	2.7–13.4	0.6	(tr.)–3.8	0.4	0.4
Taft[2] z Monzonite	35.4	26.5–39.5	33.0	27.4–36.7	28.3	22.6–33.1	3.0	1.7–4.7			0.2	Tr.
Sentinel Granodiorite	18.5	8.8–25.4	7.7	1.1–13.9	52.2	43.4–58.8	12.3	7.1–24.2	7.3	1.2–15.9	0.8	0.9
alf Dome Quartz onzonite	25.7	17.9–32.4	25.1	18.4–32.6	39.6	32.3–47.7	5.3	1.6–9.5	2.7	0.1–9.7	0.8	0.7

mn value listed for accessory minerals.
e aft Quartz Monzonite, the volume of myrmekite ranges between 0.5 and 5.7 percent; significant amounts of sericite are also present in m pecimens.

on, are enclosed in microperthite, exhibiting t'ghost zoning." Replacement features, includ- ioclase fringed with albite or myrmekite, ori- agioclase shreds enclosed in microperthite, and crogranular areas, suggest that a residual liquid rd late in the pluton's history of crystallization these features.

Granodiorite

Sentinel Granodiorite has been divided into a r type and an eastern type, with a medial zone g mineralogic features from both border lafic minerals in specimens from the eastern the Sentinel pluton show a crude foliation not the western part. Green hornblende generally poikilitic texture and infrequently surrounds d remnants of clinopyroxene in the eastern yroxene was not noted in specimens of the r type.

astern and medial parts of the intrusive body, ed as one group, are significantly more basic he western part of the intrusion. This may be lt of assimilation of once more extensive bodies apitan Granodiorite and Taft Quartz Monzo- ing emplacement of the Sentinel Granodiorite at that time, may have been essentially of iorite composition. The mean values of the rocks (Appendix F) show the western type granodiorite while the eastern type is barely uartz diorite field; the four samples from an e medial area were all of quartz diorite com-

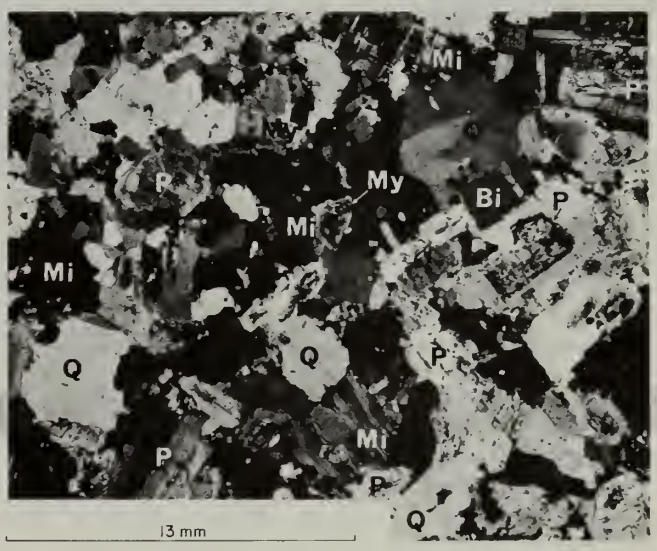


Photo 4. Granodiorite of Arch Rock. Photomicrograph of the granodiorite of Arch Rock showing altered sericitic zones in the plogioclase (P) (right center) ond poikilitic noture of the microcline (Mi). Excellent grid twinning is shown ot the top ond lower center of the photograph. Occosional biotite floke (Bi).

Half Dome Quartz Monzonite

The texture is hypidiomorphic granular, but seven of the 24 specimens examined have an interstitial groundmass composed of grains less than ⅜ mm in diameter, comprising 10 to 20 percent of each slide. The most distinctive mineral in the slides examined is

Phata 5. Granite walls surraunding Yasemite Valley; El Capitan promontory an the left ond Bridolveil folls ocross the Volley. Distinctive I (center background) marks the eastern end of the U-shaped valley. *Photo by Mory Hill.*

poikilitic microcline, which exhibits grid twinning in irregular veins and "ghost zoning" in those grains which contain numerous shreds of aligned plagioclase grains. Euhedral biotite commonly occurs in clusters with sphene and accessory minerals; hornblende is about as abundant as biotite (averaging about 2.7 percent by volume). Hornblende infrequently includes a corroded relic of clinopyroxene. With two exceptions, the modes were in the compositional range of a quartz monzonite.

SUMMARY

Table 4 summarizes the mean value of the modal analyses made in this study and compares these with a recent study by F. C. W. Dodge (Lee and Dodge, 1964) for six lithologic units in the Yosemite Valley area.

The mean values listed in Table 4 that were obtained by the writer present the arithmetic average of the tabulated modes for each intrusive unit. Figure 3

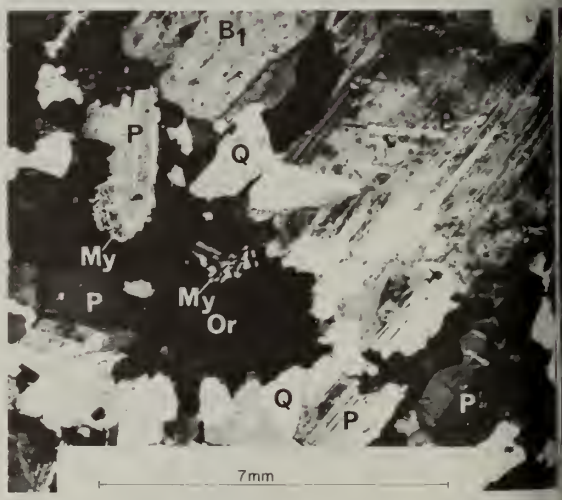
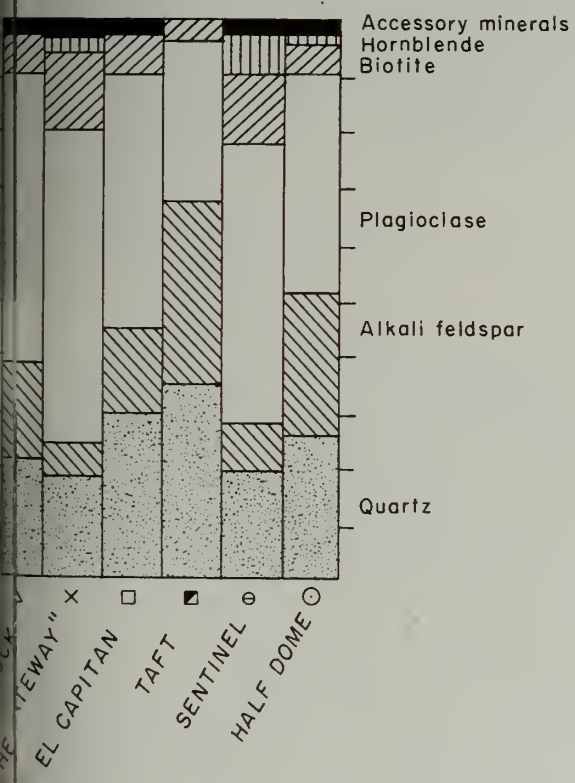


Photo 6. Quartz diorite of "The Gateway". Phatamicro quartz diorite of "The Gateway," showing a narmal ascillat plagioclose crystal (P) with polysynthetic twin lamellae af unif ness and a small amaunt af myrmekite (my) at the grain

Table 4. A comparison of average modal composition and percent anorthite in plagioclase crystals of specimens of granitic rock from intrusive bodies in the Yosemite Valley area, California.

	ARCH ROCK		"THE GATEWAY"		EL CAPITAN		TAFT		SENTINEL		HALF DOME	
	I	II	I	II	I	II	I	II	I	II	I	II
----------	31.9	21.2	19.3	18.4	31.5	30.4	35.9	35.4	20.7	18.5	28.0	25.7
----------	14.3	18.0	0.9	3.1	17.5	15.6	36.7	33.0	7.2	7.7	18.6	25.1
----------	41.8	52.5	57.9	58.4	42.2	45.2	25.4	28.3	50.7	52.2	41.9	39.6
----------	--	6.9	--	13.8	--	7.0	--	3.0	--	12.3	--	5.3
----------	--	--	--	3.7	--	0.6	--	--	--	7.3	--	2.7
c minerals)-----	12.0	6.9	21.9	17.5	8.8	7.6	1.0	3.0	21.4	19.6	11.5	8.0
essories--------	--	0.6	--	1.2	--	0.4	--	0.2	--	0.8	--	0.8
c accessories----	--	0.8	--	1.4	--	0.4	--	tr.	--	0.9	--	0.7
composition----	25–37	17–28	32–50	22–38	22–32	20–34	10–25	9–25	38–48	22–49	25–40	22–45
An)												
specimens------	(3)	(2)	(5)	(6)	(22)	(19)	(5)	(9)	(17)	(19)	(17)	(13)

analyses by F. C. W. Dodge (Lee and Dodge, 1964).
nalyses by A. R. Smith (1958).



Histogram showing average minerol content of Yosemite plons.

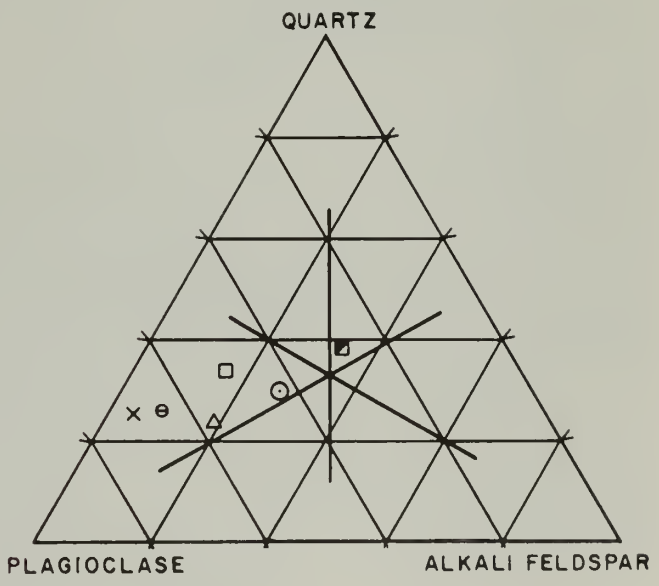


Figure 4. Ternary plot of average felsic content of six Yosemite Valley plutons.

Photo 7. Half Dome from Yosemite Volley, The Royal Arches, southern face of North Dome, outcrops at the left. The Ahwohnee H the foreground. *Photo by Mary Hill.*

Classification by Calkins	Average modal classification
Biotite Granite of Arch Rock	[1]Granodiorite of Arch Rock
Granodiorite of "The Gateway"	Quartz Diorite of "The Gateway"
El Capitan Granite	El Capitan Granodiorite
Taft Granite	Taft Quartz Monzonite
Sentinel Granodiorite	[2]Sentinel Granodiorite
Half Dome Quartz Monzonite	[3]Half Dome Quartz Monzonite

[1] The biotite granite of Arch Rock was not extensively sampled. From two modes available here and from a thin section examination made by Brooks (1958) in extending the pluton south of the Merced River, its composition is that of a granodiorite.

[2] The volume percent of K-feldspar relative to the total feldspar content of the Sentinel Granodiorite falls on the line between quartz diorite and granodiorite. On the basis of the modes now available, Calkin's original classification is still valid. As shown in Appendix F, however, the mean values for the western part show more quartz and alkali feldspar than do the "more typical" specimens from the medial and eastern parts of the Sentinel pluton.

[3] The Half Dome Quartz Monzonite was not sampled enough in this study to determine a representative mean. Dodge's sampling (Lee and Dodge, 1964), somewhat more extensive, indicates that the composition of the Half Dome pluton lies near the borderline between quartz monzonite and granodiorite.

is a histogram of this mean value for compari tween granitic units listed in the order of their age; i.e., oldest to the left, youngest to the rig

Mr. Dodge made his analyses on staine (Bailey and Stevens, 1960). The modal val tained by the writer were from normal thin as described under "*Methods of Study*." A cl relation of the average composition is apparent of the six mutually sampled plutons.

On the basis of the combined number of sam which modal analyses were done independent following reclassification is suggested as bein descriptive of four granitic intrusive units in t semite Valley area, than Calkins' (1930) no ture. Classification of the Sentinel Granodior Half Dome Quartz Monzonite remains as Cal named them on the basis of the quantitative da sented here.

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. Yosemite Valley Flaor, viewed east from Half Dame with Sentinel rack an the left and the steep face of El Capitan in the center d. *Phata by John Burnett.*

APPENDIX

A. Modes of specimens from the granodiorite of Arch Rock. (Volume percent)

Sample number	Quartz	Alkali feldspar	Plagioclase	Biotite	Hornblende	Accessory minerals: Opaque	Accessory minerals: Non-opaque
450-1-6*	19.8	18.7	54.3	5.7	--	0.7	0.8
-6	18.9	17.6	56.1	6.3	--	0.4	0.7
-5	23.1	17.8	49.9	7.7	--	0.6	0.9
Mean	21.2	18.0	52.5	6.9	--	0.6	0.8

* Two counts were made on slide 6; both are presented for comparison, but the average was used in calculating the mean.

B. Modes of specimens from the quartz diorite of "The Gateway." (Volume percent)

Sample number	Quartz	Alkali feldspar	Plagioclase	Biotite	Hornblende	Accessory minerals: Opaque	Accessory minerals: Non-opaque
450-1-48	19.2	10.0	53.6	11.6	4.3	0.7	0.6
-47	9.2	1.0	67.8	16.2	2.7	1.6	1.5
-46	25.7	3.6	52.6	13.7	2.7	0.4	1.2
- 2*	17.0	1.8	56.0	14.0	6.0	3.0	2.2
- 3*	14.4	1.5	66.4	12.6	3.5	0.6	1.0
- 1	24.9	0.5	54.2	14.9	3.2	0.6	1.7
Mean	18.4	3.1	58.4	13.8	3.7	1.2	1.4

* Approximately 500 points.

C. Modes of specimens from El Capitan Granodiorite. (Volume percent)

	Sample number	Quartz	Alkali feldspar	Plagioclase	Biotite	Hornblende	Accessory minerals: Opaque	Accessory minerals: Non-opaque
a	450-1- 52	24.7	4.1	62.4	8.0	--	0.5	0.3
a	- 49	24.3	9.0	52.2	13.4	0.2	0.3	0.6
a	- 53	28.5	12.0	48.3	9.7	0.9	0.2	0.4
a	- 8*	24.4	13.8	48.3	12.4	--	1.1	--
a	- 17*	24.9	16.0	52.7	6.1	--	0.4	--
a	- 44	31.1	11.5	48.8	8.0	--	0.1	0.5
a	- 43	31.2	3.9	55.7	8.5	--	0.3	0.4
a	- 18	29.1	7.4	54.7	7.8	--	0.4	0.6
a	- 15	25.7	12.4	50.4	10.8	--	0.3	0.4
a	-129	29.9	20.1	46.1	3.5	--	0.3	0.1
a	-130	33.5	18.0	44.6	3.4	--	0.1	0.4
a	- 38A	37.8	20.1	39.0	2.7	--	0.2	0.2
a	- 76	36.0	20.3	37.2	6.0	--	0.3	0.2
a	(Mean)	29.3	13.0	49.3	7.2	Tr.	0.3	0.4
b	450-1- 19*	37.5	22.3	35.3	3.4	1.1	Tr.	0.4
b	- 20	25.3	20.5	42.5	6.5	3.8	0.3	1.1
b	- 22*	23.9	22.0	41.4	9.0	2.9	0.3	0.5
b	- 56	29.5	23.4	36.7	7.8	1.6	0.3	0.7
b	(Mean)	29.0	22.1	38.9	6.7	2.3	0.2	0.7
c	435-1- 75†	43.5	20.1	29.5	5.4	0.1	0.4	1.0
c	-133	36.4	20.3	34.0	7.7	--	0.6	0.9
c	(Mean)	40.0	20.2	31.8	6.5	Tr.	0.5	0.9
	Average	30.4	15.6	45.2	7.0	0.6	0.4	0.4

[a] Main body of El Capitan Granodiorite.
[b] Between Rocky Point and Indian Village, on north side of Yosemite Valley.
[c] Quartz monzonite facies of El Capitan Granodiorite included within the Sentinel Granodiorite.
* Approximately 1000 points counted.
† Collected and counted by E. R. Brooks. (Brooks, 1958)

D. Modes of specimens from the Taft Quartz Mon (Volume percent)

Sample number	Quartz	Alkali feldspar	Plagioclase	Biotite	Myrmekite	Sericit
450-1 63	36.3	31.2	29.8	2.4	3.3	0.2
- 64	44.9	27.9	22.6	4.3	*	*
- 62	26.5	37.9	33.1	2.4	5.7	0.1
- 59	33.8	37.5	27.0	1.7	4.5	0.1
- 11	34.4	27.4	33.1	4.7	1.7	*
- 25	34.2	36.7	26.3	2.3	*	*
-126	38.2	33.7	25.5	2.6	*	0.8
-128	39.5	29.6	26.9	3.8	0.5	0.3
-118	30.9	35.3	30.2	3.3	*	*
Mean	35.4	33.0	28.3	3.0	--	--

* Not counted as a separate component.

E. Modes of specimens from Sentinel Granodiori (Volume percent)

	Sample number	Quartz	Alkali feldspar	Plagioclase	Biotite	Hornblende	Accesso Opaque
a	450-1-116	19.2	9.2	46.8	10.6	11.1	0.9
a	- 57	25.4	8.3	52.8	11.3	1.2	0.8
a	- 37	23.2	9.1	51.4	11.5	3.5	0.1
a	-132A	22.7	13.9	47.3	9.6	5.2	0.4
a	- 78	22.6	11.8	46.5	10.8	6.8	1.0
a	- 98	24.4	7.0	45.8	11.6	9.1	1.0
a	- 96	21.6	10.1	53.4	10.2	3.8	0.2
a	114	23.1	10.2	52.0	8.4	4.9	0.6
b	- 35*	24.6	3.2	58.7	7.1	3.5	1.1
b	- 94*	13.6	4.3	60.0	15.0	4.0	0.7
b	- 82	13.7	1.5	55.6	19.2	6.9	1.6
b	-134	8.8	7.9	56.5	9.1	15.9	1.1
c	-112	12.9	2.8	58.8	16.8	6.7	0.4
c	-113	14.4	1.1	48.4	24.2	9.8	1.2
c	- 91	18.9	11.2	56.0	10.0	2.6	0.5
c	-140	18.7	8.1	43.4	14.0	10.8	0.5
c	- 90	13.8	7.3	51.9	13.6	11.9	1.1
c	-109*	16.1	10.3	50.5	11.9	8.6	1.0
c	- 99	13.6	9.3	55.5	8.1	12.0	1.1
	Mean	18.5	7.7	52.2	12.3	7.3	0.8

* The average of two different thin sections of the same specin (
discussion under *Method of Classification*).
[a] Western type.
[b] Medial zone.
[c] Eastern type.

F. The mean volume percent of minerals in the weste medial, and eastern types of the Sentinel Granodiori

Type	Quartz	Alkali feldspar	Plagioclase	Biotite	Hornblende	Accessory Opaque
(a) Western	22.7	9.9	49.6	10.5	5.7	0.8
(b) Medial	15.2	4.2	57.7	12.6	7.8	1.1
(c) Eastern	15.5	7.2	52.1	14.1	9.0	0.9

G. Modes of specimens from the Half Dome Quartz Monzonite.
(Volume percent)

Sample number	Quartz	Alkali feldspar	Plagioclase	Biotite	Hornblende	Accessory minerals: Opaque	Accessory minerals: Nonopaque
450–1– 28	22.9	20.6	43.0	9.5	2.1	1.0	0.9
– 29	32.4	22.3	39.3	4.0	1.2	0.3	0.5
– 30	26.5	29.6	37.6	4.8	0.1	0.8	0.6
–105	25.2	32.6	38.9	2.0	0.5	0.5	0.3
–100	23.0	28.4	37.1	5.3	3.8	1.4	1.0
–104*	18.5	22.8	44.4	3.8	8.1	1.5	0.9
– 32	28.3	23.8	37.6	7.4	1.4	0.6	0.9
– 33	29.1	23.2	39.4	6.4	0.9	0.5	0.5
– 85	17.9	22.7	43.4	4.4	9.7	0.8	1.1
– 84	30.9	18.4	47.7	1.6	1.0	0.2	0.2
–102	27.5	25.8	32.3	8.6	3.3	1.2	1.3
– 31	28.2	30.8	36.4	2.7	0.9	0.6	0.4
– 26R†	24.3	26.0	37.3	8.0	1.9	1.6	0.9
Mean	25.7	25.1	39.6	5.3	2.7	0.8	0.7

* Thin section contains many voids.
† Sample collected by E. R. Brooks from Half Dome.

THE ORIGIN OF TUSCAN BUTTES AND THE VOLUME OF THE TUSCAN FORMATION IN NORTHERN CALIFORNIA*

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ABSTRACT

Tuscon Buttes are two prominent hills rising 500 feet above surrounding flat-topped ridges about 10 miles northwest of Red Bluff in northern California, near the head of Sacramento Valley. They intrude the upper Pliocene Tuscan Formation, a widespread accumulation of tuff breccia and subordinate tuff, sand, and gravel that originated from a series of eruptive centers near the present crest of the southernmost Cascade Range.

Tuscan Buttes were reported in 1933 by C. A. Anderson to be erosional remnants of Tuscan rocks capped by a remnant dipping flow of hornblende andesite, which was immediately underlain by a distinctive breccia formed of volcanic mud. Detailed mapping now shows that the buttes are core intrusive plugs surrounded by a mantle of breccia that originated chiefly by spalling and sloughing from the intruding plugs.

The author's estimate, in 1961, of a 250-cubic-mile volume for the Tuscan Formation was based on a contour map of its exposed thickness. One of the assumptions made in the estimate was that erosion had lowered the upper surface of the Tuscan Formation only slightly if at all. This assumption is supported by the present conclusion that Tuscan Buttes did not form by erosion of a thickness of 2,000 feet of rock from the surrounding area.

INTRODUCTION

The continental Tuscan Formation of late Pliocene age is discontinuously exposed throughout an area of about 2,000 square miles east of the northern Sacramento Valley in California (fig. 1). Originating largely from a belt of isolated eruptive centers extending north-northwestward from Butt Mountain, in the southernmost Cascade Range, vast sheets of laharic breccia spread westward and coalesced. Intermittent flows of lava were extruded, interspersed with violent eruptions of ash. During intervening periods of quiescence numerous streams eroded the tuff breccias, depositing volcanic sand and gravel throughout all of the area now covered by the Tuscan Formation, but principally in its western and southern parts. The Tuscan Formation so formed consists of up to 2,000 feet of tuff breccia and interlayered volcanic flows, breccia, sand, gravel, and tuff.

Part of the formation was first briefly described by Whitney (1865), although he assigned no name to it. J. S. Diller provided several more extensive descriptions of the unit, referring to it alternately as the "Tuscan tuff" (1894, 1906) and "Tuscan formation" (1892, 1894, 1895). C. A. Anderson (1933) has given the most detailed description of the unit to date, identifying it as the Tuscan Formation, by which name it since has been known. The entire formation recently has been mapped at a scale of 1:250,000, as part of the Westwood, Chico, and Redding sheets of the Geologic Map of California (Lydon, Gay, and Jennings, 1960; Burnett and Jennings, 1962; Strand, 1962).

These maps provided data from which the volume of the Tuscan Formation was estimated to be 250 cubic miles (Lydon, 1961).

The mode of origin of Tuscan Buttes, two prominent hills rising above the principal surface of the Tuscan Formation, is important in establishing the validity of this volume estimate. Anderson (1933, p. 231-232) had concluded that Tuscan Buttes are erosional remnants:

> ". . . the buttes merely represent homoclinal dipping beds of the Tuscan formation capped by a lava flow . . . It [the flow] may have been related to a volcano near the present site of Tuscan Buttes, but certainly the present Tuscan Buttes are only an erosional feature and not remnants of a volcanic cone."

If Anderson's conclusions are correct, the Tuscan Formation in this area must have been eroded to a depth of at least 500 feet, inasmuch as Tuscan Buttes stand that high above the average level of the surrounding ridge tops, and the 250-cubic-mile volume estimate would be too small.

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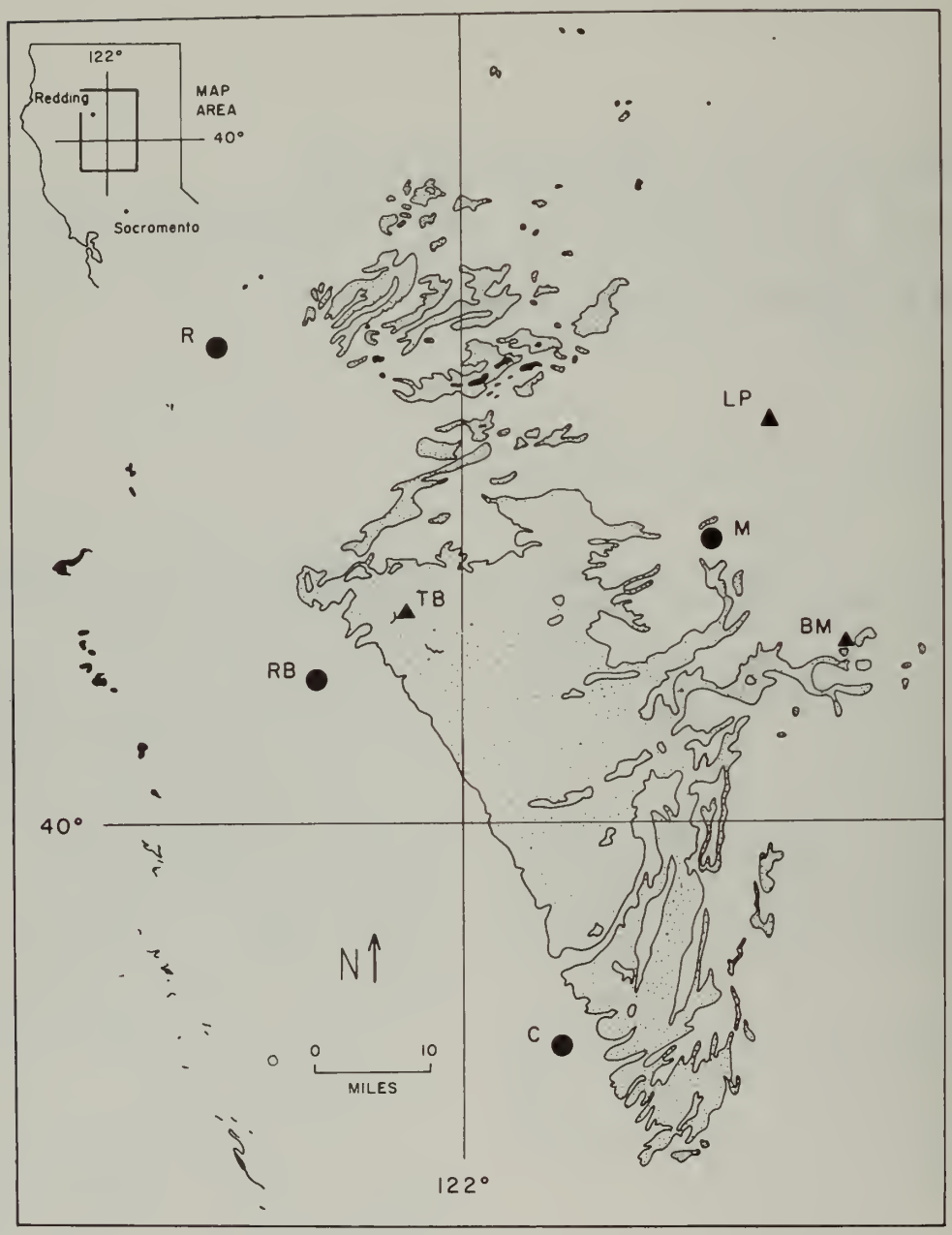


Figure 1. Map showing approximate distributian af the Tuscan Formotian (stippled) and of the majar tuff units associated with it. Towns indicated by dots are Redding (R), Red Bluff (RB), Chico (C), and Mineral (M); triangles represent Lassen Peok (LP), Butt Mountain (BM), and Tuscan Buttes (TB). The tuff expasures south of Redding and sauthwest of Tuscan Buttes are the Namlaki Tuff Member of the Tuscan and Tehoma Farmations. The tuff expasures east ond nartheast af Redding are not Namlaki, but an intrafarmatianal welded tuff fram a saurce narthwest af Lassen Peok.

author mapped Tuscan Buttes in March 1964 2), and concluded that they are two volcanic that intruded the Tuscan Formation, and that o not indicate substantial planation of the sur- f the Tuscan. These conclusions are in accord he volume estimate of 250 cubic miles. This describes the results of that study.

Campbell, C. W. Chesterman, and F. F. Davis California Division of Mines and Geology read nuscript, and many helpful suggestions were oy D. W. Peterson of the U.S. Geological Sur- o each of these men the author expresses his de.

TUSCAN BUTTES

can Buttes are two closely-placed yet distinct aving steep sides and rounded tops. They are n in a northwest-southeast direction, and the nt of each has two sharp knolls aligned in an est direction. The principal summits of each ain elevations of 1,868 and about 1,780 feet. an Buttes are in Tehama County about 10 miles ast of Red Bluff, south of the highway to Las- olcanic National Park, and form one of the onspicuous landmarks in the area (figure 1). bear superficial resemblance to volcanic cones o 1).

. Tuscan Buttes viewed from the south, showing their super- remblance to volcanic cones. Breccia blocks in foreground are d when softer tuff matrix is removed by wind and rain. *John L. Burnett.*

Geology

upper Pliocene continental Tuscan Formation rmably overlies marine sedimentary rocks of per Cretaceous Chico Formation in the foot- st east of the northern Sacramento Valley. ier elevations, west of Lassen Peak, Mineral, t Mt. (fig. 1) the Tuscan is overlain by flows site and basalt; adjacent to and in the valley, ered by gravels, terrace deposits, and alluvium. Sacramento Valley subsurface, the Tuscan on interfingers with the nonvolcanic conti- nental Tehama Formation. A distinctive pumice tuff, the Nomlaki Tuff Member, is exposed near the base of both the Tehama and the Tuscan Formations.

In the area mapped, tuff breccias of the Tuscan Formation are the dominant rock type. Minor beds of volcanic sediment, pumiceous tuff, and volcanic flow rock are included in the formation. The underlying Chico Formation is exposed in only a small part of the map area. Post-Tuscan rocks include the andesitic flow, breccia, and plugs that together comprise Tuscan Buttes, and scattered small flows and intrusive masses of olivine basalt. Small patches of alluvium insignificant to this study were not mapped.

Chico Formation

Near the center of the area outlined by the outcrops of Nomlaki Tuff (fig. 2), sandstone and shale lithologically similar to the Chico Formation of Late Cretaceous age are exposed intermittently in a stream bottom. The sandstone is a yellowish gray-green lithic wacke composed of particles in the fine- to medium-sand size range. It occurs in resistant beds 3 to 12 inches thick separated by a few inches to several feet of less resistant, conchoidally fracturing shale. These sparse exposures of Cretaceous rock are noteworthy especially for the deformation they have undergone, as indicated by their steep dips to the west.

Tuscan Formation

Nomlaki Tuff Member. A soft, light gray, pumiceous dacitic tuff 25 to 65 feet thick is exposed in the southwestern part of the map area. Careful inspection of its southernmost contact failed to reveal any clear evidence of faulting, but inasmuch as the tuff is abruptly terminated here, a fault is assumed to have been the cause. An identical tuff 20 feet thick is exposed 2,000 feet farther south at an elevation of 950 feet, in the northeast wall of a large semi-circular depression in which are located Tuscan Springs. Except for one minor fault offset, this tuff can be traced continuously a half mile southwestward, to its position near the base of the Tuscan Formation where Anderson (1933, fig. 3 and p. 224) had placed it in a measured section at Tuscan Springs and identified it as the Nomlaki Tuff.

The type section of the Nomlaki Tuff is near Flournoy on the west side of the Sacramento Valley, 28 miles southwest of Tuscan Springs; it is unexposed throughout the entire intervening distance. Anderson and Russell (1939, p. 245) suggested that a gray welded tuff intermittently exposed east of Redding (fig. 1) represents near-source material of the Nomlaki. Detailed study of this welded tuff by the present author indicates that it is a different tuff from the Nomlaki. The source of the eastern tuff is in the large exposure of Tuscan Formation northwest of Lassen Peak (fig. 1); it was violently expelled southwestward down a wide Tertiary canyon, and, at about 122° longitude, was deflected northwestward. Its distal end came to rest northeast of Redding, after having travelled about 30 miles.

The tuff exposed at Tuscan Springs and Tuscan Buttes resembles closely the tuff comprising the bulk of the Nomlaki, and it is more likely that this mate-

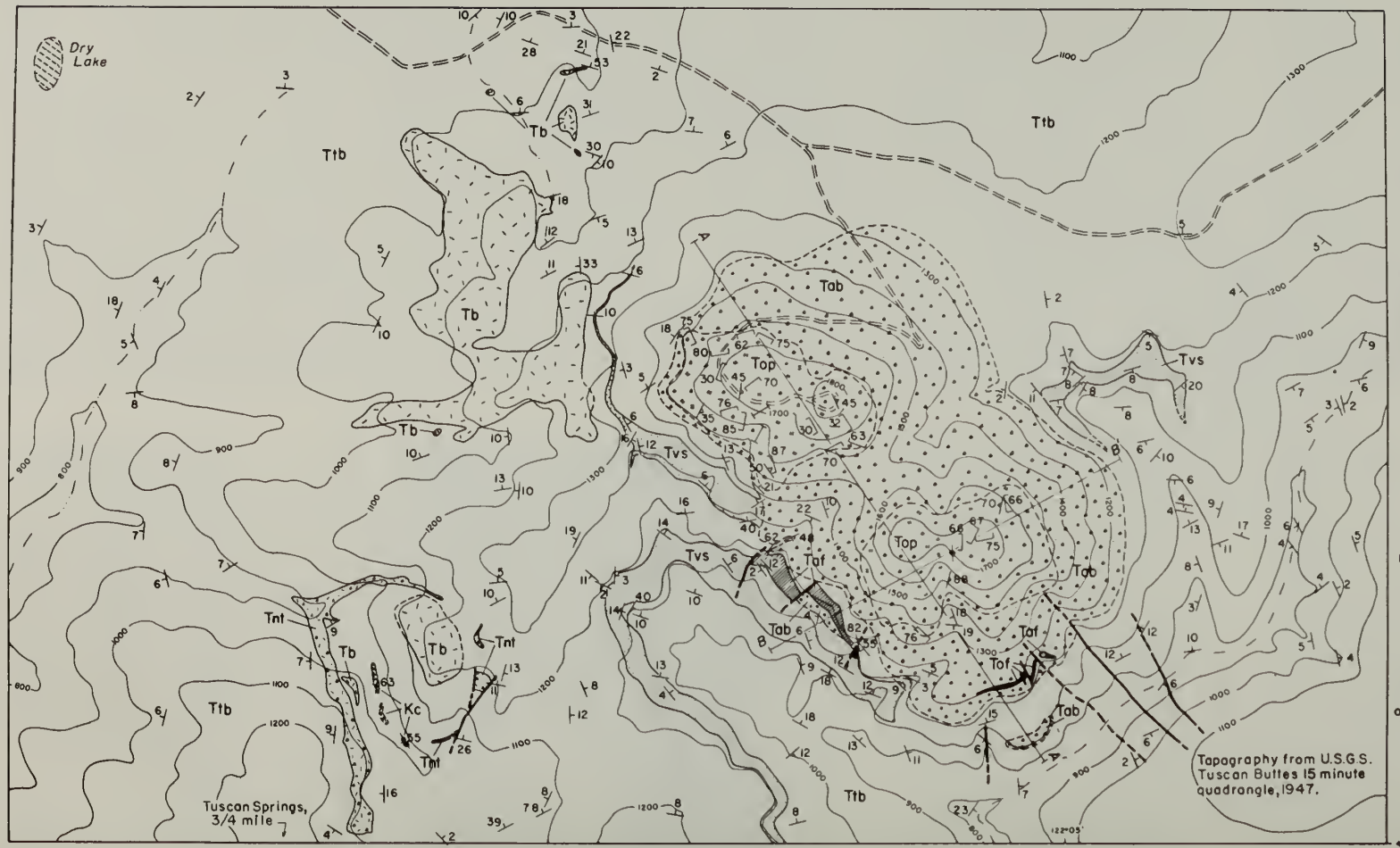


Figure 2. Geological map of Tuscan Buttes, Tehama County, northern California. (Cross sections along lines A-A' and B-B' are shown in fig. 3.)

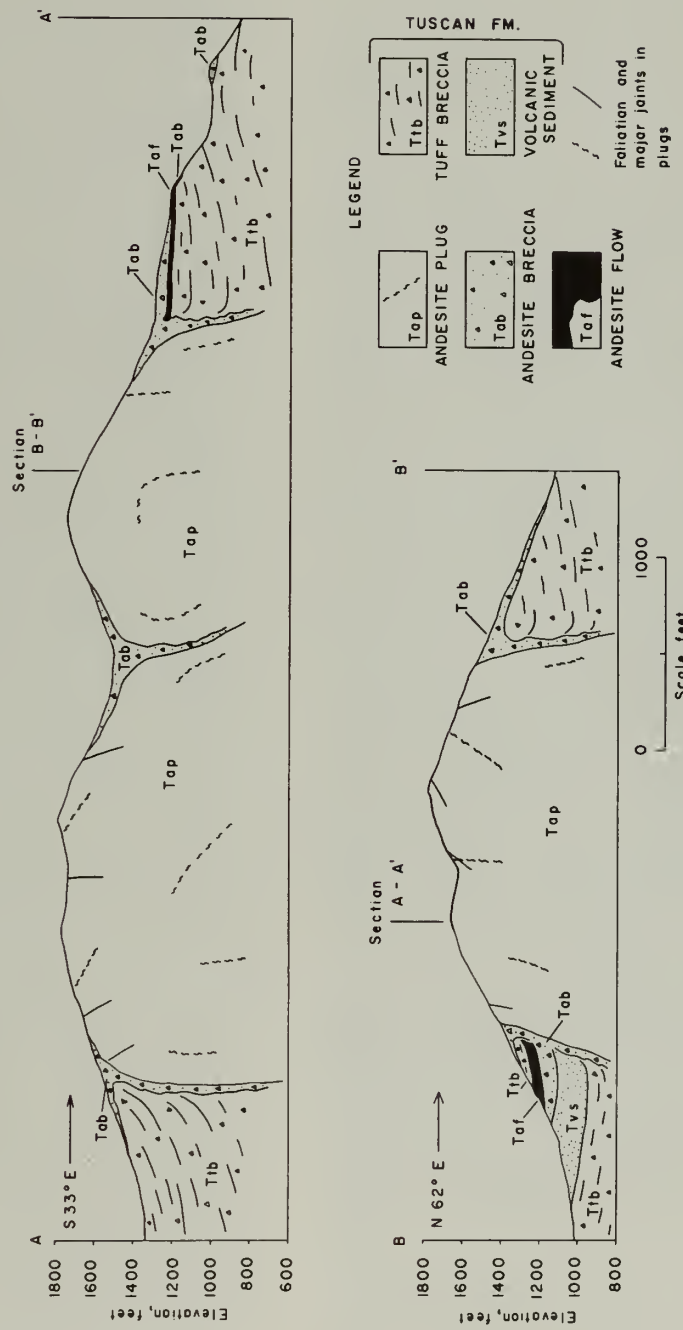


Figure 3. Geological cross sections through Tuscan Buttes.

rial, rather than that east of Redding, is the near-source equivalent of the Nomlaki. Additional Nomlaki Tuff was noted by Anderson (1933, fig. 3) in a measured section on Antelope Creek, almost 5 miles southeast of Tuscan Buttes, where it is exposed intermittently for about 2½ miles along the canyon bottom. Parts of it closely resemble the Nomlaki, but it cannot be traced directly to either the Nomlaki type section or the tuff at Tuscan Springs or Tuscan Buttes. The tuff at Antelope Creek might possibly represent explosive activity not directly related to that of the Nomlaki, a not improbable consideration in view of the many massive tuffs present in the Tuscan Formation.

In the Tuscan Buttes area, the Nomlaki Tuff consists of about 20 percent colorless glass shards, 30 percent white pumice, 40 percent devitrified glassy matrix, 8 percent zoned and twinned andesine crystals, and 2 percent hypersthene, green hornblende, and magnetite. It is generally free of lithic fragments. No evidence of welding is apparent in thin section, although glass shards are annealed to plagioclase crystal faces and glass has penetrated broken crystals along cleavage directions.

The largest exposure of Nomlaki Tuff shown on the geological map (fig. 2) is typically light gray in color, but 1 to 8 feet of its upper portion have been oxidized to pink or red. The top of the tuff locally has been scoured and channeled by tuff breccia, and at one locale it grades upward into sandy tuff and then tuff breccia; ordinarily, however, the tuff has merely a conformable contact with the rocks above. The base of the Nomlaki Tuff is not well exposed, but at one outcrop, sandstone and conglomerate underlying the tuff were baked to a depth of one foot.

Three small outcrops of Nomlaki Tuff lie east of the principal exposure. The two lower outcrops may once have been part of the same ash flow, and presumably are correlative with the principal exposure of tuff. The upper outcrop, however, grades laterally into a resistant bed of tuff breccia about 2 feet thick that can be traced to a position about 25 feet above the top of the middle outcrop.

Under the microscope, this rock is seen to contain a variety of accidental volcanic-rock fragments, pumice, and broken phenocryst fragments in a turbid brown matrix of devitrified glass that also contains magnetite dust and grains, euhedral microlites, and slightly deformed to undeformed glass shards. Augite and hypersthene are present as phenocryst fragments, but hypersthene and enstatite are the only pyroxenes among the microlites. Andesine occurs as both fresh phenocryst fragments and microlites. Rare crystals of green hornblende and red biotite were observed.

Volcanic Sediment. Only the major sedimentary units are differentiated on the geological map. Many small lenses or layers of sedimentary rock, a few inches to a few feet thick, are not shown separately because of poor exposures or lack of continuity of the units themselves. Indeed, most of the attitudes shown in tuff breccia on the map were taken on thin interbedded sedimentary layers. The component materials of the sedimentary rocks observed are exclusively volcanic in character, with one exception noted below. Thinly laminated clay and silt are common, l dominant types are well-bedded sandstone an massive conglomerate. Small interbeds of tuff e are included in the separately mapped volcan ments.

White diatomaceous ash—the first reporte the Tuscan Formation—is exposed adjacent southernmost portion of the northwestern plug layers totaling 3 feet in thickness dip 21°N more ashy portions of this outcrop contai sponge spicules and fragments of the fres diatom *Cymbella*. Minute layers of clean di contain little ash, abundant fragments of C (perhaps *mexicana*), *Epithemia*, and sponge s and rare fragments of *Melosira granulata*, *Eunc* and one or two other genera not identified. The fragmented nature of the diatoms suggests th were reworked before arriving at their presen tion. Dr. G. Dallas Hanna (written communi July 1964) confirmed these identifications, and that these diatoms indicate a deposit of Pliocen formed in a lake of mild alkalinity.

Tuff Breccia. In the area mapped, the Tusca mation consists dominantly of tuff breccia, use used in this report in the broad sense given Glossary of Geology and Related Sciences (Am Geological Institute, 1957, p. 306): "A type canic breccia in which the tuffaceous matrix b the blocks is abundant and comprises between 25 and 75 percent by volume." Characteristical proportion of matrix, sizes of non-matrix partic lithologic types represented among the fragmen rapidly from place to place in the same flow a tween flows. In general, the colors of the tuff b are in shades of gray, brown, and purple. The s non-matrix particles range from just larger th or sand to blocks several feet across, but the a probably is between 2 and 4 inches. Andesi basalt are the principal broad classes of rock fra present; plagioclase, olivine, pyroxene, and horn phenocrysts in varying proportions and sizes, to with color and degree of vesicularity, provide th for further classification. Extensive sampling a tailed study would be needed to determine wi authority the proportions of rock types comprisi Tuscan tuff breccias in the map area.

Although the vast majority of the tuff bree older than the andesite plugs, two outcrops s that small Tuscan lahars were laid down afte Above the smallest faulted segment of andesit southwest of the southeastern plug, poorly e volcanic sedimentary rocks dip 55° and 82° SW result of forceful emplacement of the plug; these sediments were eroded and then covered by di flows of tuff breccia similar to those that compr bulk of the Tuscan Formation in this area (ph

Small interbeds of cream to buff-colored t exposed locally among the tuff breccias, esp north and northwest of the principal basalt fl this same area, numerous anastamosing dike-lik jections of tuff breccia a few inches wide rise 2 inches above the surrounding tuff and tuff b They trend generally northwest or west, an steeply to the northeast or north. The projectio

o megascopically visible internal structure, and
eraordinarily well-cemented.

in section of one showed abundant fragments of
stinct types of vesicular glassy pyroxene basalt
altic andesite in a turbid matrix of slightly devit-
brownish glass. No flow structure in the matrix
parent under the microscope, nor did the matrix
n any essential crystals; hence the projections
umed to represent the well-cemented walls of
aled joints along which groundwater once

ddition to tuff and tuff breccia, the Tuscan For-
in the map area also includes a few small flows
trusive masses of pyroxene andesite and basalt.

e

eral Description and Petrography. Hornblende
e, which comprises the mass of the plugs them-
the breccia derived from them, and the flows
e base of the southeastern plug, is unlike any of
k types present as flows or breccia blocks in the
nding Tuscan Formation. It is medium-light
when fresh, but most of it has been oxidized to a
t pinkish color.

er the microscope, partially resorbed pheno-
of basaltic hornblende are sparingly present in a
of trachytic microlites of andesine and labra-
sparse colorless glass, and dust and minute grains
k magnetite. A nearly isotropic, colorless min-
ith refractive index n = 1.487 ± .002, is present
small amounts; X-ray diffraction analysis shows
e α-cristobalite (Eugene B. Gross, written com-
ation, August 1964).

emical analysis of this rock by Clarke and Hille-
(1897, p. 195) shows that it contains about 61
t SiO_2; hence it is classed as an andesite.

esite Flow. Two isolated series of exposures of
e flow rock occur at about the same elevation
doubtedly represent a single episode of extrusive
y, if not a single flow. This rock might be a dike
but its broadly conformable relation to the sur-
ng rocks and the lack of contact effects at its
surface would seem to discount this. The rock
ascopically indistinguishable in the hand speci-
om the andesite comprising the plugs. Foliation
apparent, and crudely developed polygonal
g is present only locally.

esite Breccia. The hornblende-andesite breccia
ily distinguished from the tuff breccias of the
n Formation by its pervasive oxidation, resulting
nk to purplish color in both the breccia blocks
atrix, and its monolithologic character, which
sts with the variable color and lithology of the
n. Much of the andesite breccia close to the
consists of tightly packed angular blocks with
bly low proportion of matrix (photo 3), al-
farther away the blocks are subangular and
comprises as much as half the rock. The brec-
mmonly is poorly exposed, consisting of col-
material loosely packed in soil, but in numerous
gullies its dip-slope character and unconform-
elation to the underlying Tuscan are clearly

In the upper part of the prominent gully separating the two plugs on the southwest side, crudely bedded andesite breccia dips gently toward the plugs. Some 50 feet in elevation below this, the breccia dips 22° SW, parallel to the slope of the topography. Between these two attitudes, which are shown on the geological map, a poorly exposed breccia dike 4 feet wide strikes N.15°W. and dips 60° E. These outcrops suggest that at least part of the andesite breccia issued from fissures in an already brecciated condition, and then flowed downslope, partially covering the Tuscan tuff breccias.

Dip-slope accumulations of andesite breccia resting unconformably on Tuscan rocks are visible in road cuts on the north slope of the northwestern plug; in the northeast-trending gully between the two plugs, the breccia is as much as 8 feet thick and contains blocks roughly oriented in the direction of flow. Other dip-slope attitudes are visible in the curved gully south of the southeastern plug. At the lowest elevation reached by the andesite breccia just west of this gully, it had disrupted and baked to a reddish color some volcanic sandstone over which it passed, indicating both elevated temperature and movement with considerable force.

The earliest extrusion of andesite breccia probably was that now exposed beneath the andesite flow southwest of the southerly plug. At least another hundred feet and probably more of Tuscan tuff breccia were emplaced afterward, before intrusion of the plugs (fig. 3).

Andesite Plug. Hornblende andesite comprising the plugs is distinguished from that comprising the breccia and flows by its massive character, which has resulted locally in steep bluffs as much as 100 feet high. Elongate hornblende crystals are sparingly distributed throughout the rock, but in a few instances they are clustered together closely enough to define a local foliation (fig. 2). Steep jointing is common in the plugs, whereas gently dipping joints are relatively rare or ill defined.

Contacts between the plugs and the Tuscan rocks that they intrude are everywhere concealed by a mantle of andesite breccia. At the southernmost edge of the southeastern plug, several patches of polished rock each several square feet in extent are exposed on the surface of an abrupt wall of andesite; polished surfaces similar to these are not found elsewhere in the plugs. They probably were formed by internal abrasion of the solid or extremely viscous peripheral portions of the plug as it rose toward the surface.

Basalt

Thin flows of small extent and several even smaller intrusive masses of medium- to dark-gray olivine basalt are exposed in a relatively broad, north-trending belt just northwest of Tuscan Buttes. Throughout much of their extent, the flows form dip slopes covered by thin, flow-jointed slabs. Presumed sources of the flows are marked by small ridges composed of jumbled accumulations of massive blocks and steeply dipping slabs of basalt. The strikes of these slabs conform to the trends of the small ridges, which vary but 10 degrees on either side of due north.

A dike of basalt, the northernmost outcrop of basalt shown on the geological map (fig. 2), has disrupted the bedding of the Tuscan rocks into which it was emplaced. Other disturbed attitudes are associated with the small flow immediately to the south and with the small intrusion just south of it. The tuff breccia and associated minor sediments in this area have been baked to a red or purplish-red color for distances of up to 200 feet from the basalt. Disturbed bedding and prominent reddish coloration of the Tuscan rocks in an area 1,500 feet west and northwest of these small intrusive masses suggests the presence there of more intrusive basalt, hidden at relatively shallow depths.

The various basalts all resemble each other megascopically. Under the microscope, abundant phenocrysts of olivine together with subordinate colorless to pale green augite are seen in a trachytic matrix of plagioclase microlites and minute crystals of colorless enstatite, augite, and magnetite. Traces of pale brown glass occupy interstices between plagioclase microlites, and traces of opal and a zeolite are found in some vesicles.

Structure

In the map area, there is no clear evidence of the two en echelon, northeast-trending anticlines that some petroleum geologists have long thought passed from Tuscan Springs northeastward through Tuscan Buttes. The eroded amphitheater of Tuscan Springs, a mile wide and 300 to 500 feet deep, is a breached asymmetrical dome that plunges to the southwest. This structure appears to be terminated, just south of the area shown on the geological map, by a northwest-trending fault that also is assumed to bound the southernmost mapped portion of the Nomlaki Tuff, although no surface indication of the fault was found at that point.

Northwest of Tuscan Buttes, again outside of the area mapped for this report, there is a suggestion of a broad gentle arch that trends northwestward. Detailed mapping in this area and east of Tuscan Buttes would be required to determine whether the plugs were emplaced near the juncture of two converging structures.

Structures clearly related to emplacement of the plugs include the few radial faults shown on the geological map, and, above the smallest segment of the andesite flow southwest of the southeastern plug, volcanic sedimentary strata that dip steeply southwestward as a result of forceful emplacement of the plug. Other structures that may have been formed by intrusion of the plugs are hard to find. If present, they are almost completely hidden by the mantle of andesite breccia that everywhere masks the contacts of the plugs with the enclosing Tuscan rocks (figs. 2 and 3). Also, such structures may be rare because the Tuscan rocks might not have been consolidated enough to sustain folds over long distances, at the time the plugs were intruded.

Vertical or near-vertical jointing is prominent in the Tuscan tuff breccias, striking most commonly from N.20°W to N.40°W. It is uncertain whether jointing originated before or after the plugs were emplaced.

Origin of the Tuscan Buttes

That the andesite forming the upper part of T Buttes is a pair of plugs, and not eroded remn a flow, is made apparent principally by the fi lations between the andesite breccia, the plug the Tuscan Formation (fig. 3).

Three subordinate lines of evidence suppo origin of the Buttes as plugs. 1. The steeply d folia (fig. 3), although rare, suggest an upward ment of magma, rather than movement of a flow a gradient. 2. The contact between the plu andesite breccia varies as much as 400 feet in ele (fig. 2); it seems improbable that a single out-p of lava could have overwhelmed such irregular t raphy and still have been confined to less tha a square mile in extent. 3. Polished rock su (photo 2) could possibly represent slip surfa

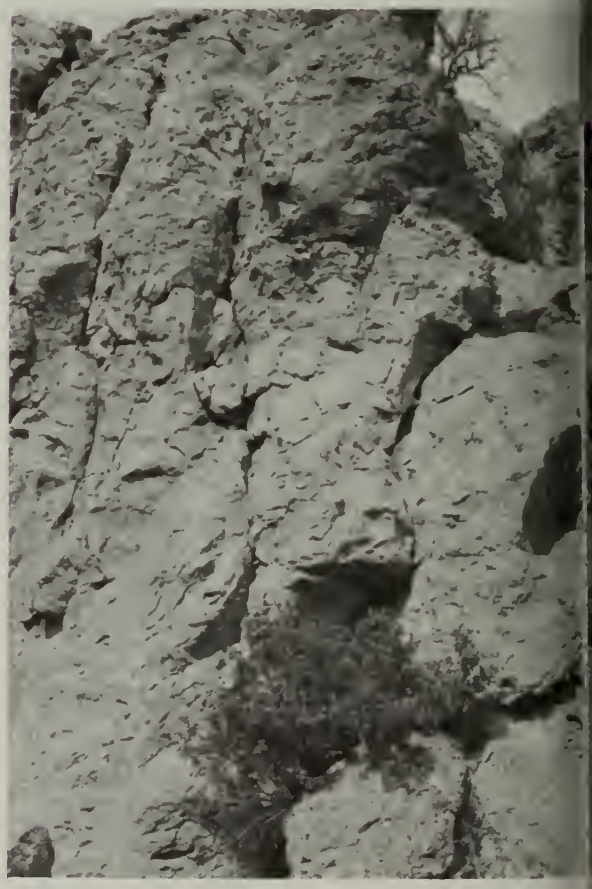
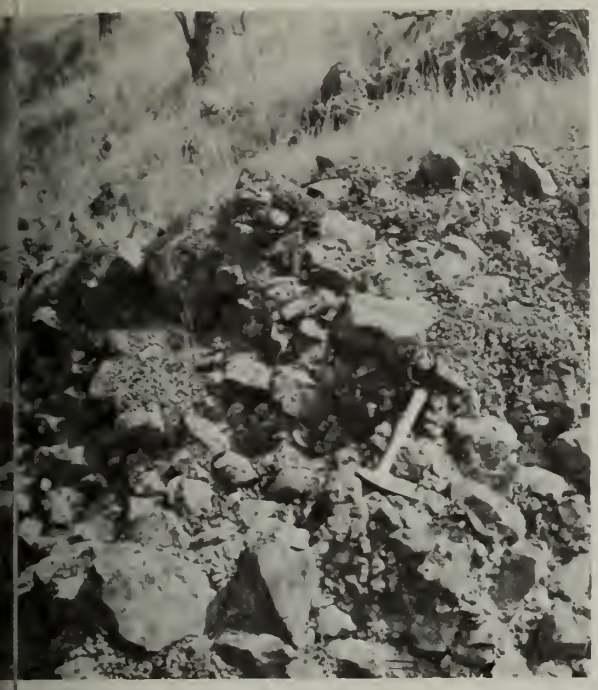


Photo 2. Polished surface (center, above bush) of plug, at so most contact of southeastern plug. Bush is 4 feet across.

slickensides formed in a lava flow. However, the c that these polished surfaces are not found in th terior portions of the massive andesite, but only sharp bluff that forms its extreme edge, strongly gests that they were formed by internal abrasio the nearly solid periphery of a rising plug.



3. Hornblende-ondesite breccio, in southwest-trending gully
plugs. Note ongulor chorocter of breccio blocks ond low pro-
of motrix.

ary of Geologic Events

position of marine sediments of the Chico For-
in in Late Cretaceous time was followed by a
nterval of erosion and moderate deformation. In
Pliocene time, lahars advancing from the east
helmed the existing landscape, forming a rela-
even surface. While lahars of the Tuscan For-
in were still moving into the area, two ash flows
citic pumic tuff (Nomlaki Tuff) were violently
ed from a source about 3,000 feet southwest of
esent site of Tuscan Buttes.

placement of the plugs that form Tuscan Buttes
receded by extrusion of andesite breccia and
possibly two flows of andesite lava. Deposition
uscan tuff breccia followed these extrusions, at
locally. Emplacement of the plugs was accom-
and perhaps followed by the formation of an
ive, taluslike mantle of andesite breccia; it prob-
originated principally by spalling and sloughing
the rising plugs, but part of it originated as ex-
ns of already brecciated material. Deformation of
rrounding Tuscan strata by the rising plugs was
ely limited. Some Tuscan tuff breccia, probably
ating from the vicinity of the plugs themselves,
eposited following this deformation.

final volcanic event in the area was the extru-
f flows of olivine basalt west of the plugs, per-
imultaneously with the intrusion of several small,
red masses of similar rock in the same area.

Volume of the Tuscan Formation

volume of 250 cubic miles previously given for
uscan Formation (Lydon, 1961, p. 24) is an ad-
ly rough estimate of the volume of the forma-
s it would have been, had no erosion occurred during or subsequent to its deposition. Hence, this "original" volume includes Tuscan-derived and Tuscan-related material, such as volcanic gravel and reworked tuff, that is now part of the adjacent and interfingering Tehama Formation. It also includes the Nomlaki Tuff Member of the Tuscan and the Tehama Formations. The volume was calculated by first plotting points of exposed thickness of Tuscan rocks on 15-minute quadrangles, then transferring these points to the Geologic Map of California (scale 1:250,000), and drawing contour lines at 100-foot intervals of thickness. Parallel northeast-trending vertical sections were then drawn at 5-mile intervals, and their areas were calculated and used to obtain a theoretical volume of 210 cubic miles for the Tuscan rocks presently exposed.

This theoretical volume, which assumes a flat-lying sheet of Tuscan rocks, must be adjusted for several factors: 1. The base of the formation is unexposed in some areas; 2. The upper surface of the formation must have had some original irregularities, and subsequent erosion; and 3. The areal extent of the formation exceeds the present outcrop area (fig. 1), mainly extending beneath the Sacramento Valley alluvial cover.

1. Base of the Tuscan Formation. In the main area of Tuscan rocks, bounded by Red Bluff, Chico, and Mineral (fig. 1), the base of the Tuscan is exposed in relatively few places, mostly in the deeper canyons. Where the base was not exposed, the volume estimate was based on only the lowest present exposures within the Tuscan Formation, ignoring the undetermined deeper part of the unit. Nevertheless, the base is exposed in enough places in this area to justify the assumption that the volume of "hidden" Tuscan is relatively small. North of a line between Red Bluff and Mineral, the base generally is well exposed. Local deviations from a gently dipping, sheetlike form as in the complex structures in the Tuscan between Red Bluff and Chico, at Mineral, and at Butt Mountain, are believed to have only a relatively minor effect on the volume calculations.

Photo 4. Steeply dipping volconic sedimentory rock in the Tuscan Formation is overloin by o dip-slope flow of ordinory Tuscon tuff breccio. View northwest. Photogroph token ot 1,150 feet elevotion, 300 feet southwest of the southeostern plug.

2. Upper surface of the Tuscan Formation. The volume calculations include material eroded from between present isolated outcrops (especially north of a line from Red Bluff to Mineral), and from the many steep-walled canyons that now cut the Tuscan. The assumption that the original constructional surface of the Tuscan has been only slightly lowered by general erosion, is supported by a) the preservation of many broad, nearly flat surfaces on intercanyon ridges, and b) the quantity of breccia blocks left behind during differential erosion of the Tuscan surface (photo 1), suggesting it has been lowered only a few feet at most. Original irregularities in the surface—local peaks and valleys—were averaged into the estimates of formation thickness.

3. Areal extent of the Tuscan Formation. The west-dipping trend of the Tuscan Formation, and the recognition of Tuscan tuff breccias in water and gas well cores, shows that it extends beneath the alluvium of the eastern part of the Sacramento Valley. Unfortunately, relatively little information on the thickness of the Tuscan Formation buried there, and on its westward extent, is available. One complicating factor is the ultimate origin of the Tuscan volcanic sands and gravels found in wells in the valley; undoubtedly partly represent lahars that were increasingly jected to the action of water as they moved f from their sources, but in addition, these sed must also represent the products of erosion fron ern canyons and gullies that must have been fo even before the first lahars reached the present e the Sacramento Valley. A further complication interfingering of the Tuscan breccias and sedi beneath the Sacramento Valley with the nonvo sediments of the Tehama Formation, which being deposited simultaneously from the wes north. This interfingering took place through broad zone down the center of the valley, so th western border of Tuscan rocks would be hard fine, even if it were exposed. It is believed that few tens of cubic miles of Tuscan rocks are h beneath the Sacramento Valley.

The estimated volume of 210 cubic miles w justed to the 250 cubic miles by adding an admi arbitrary figure of 40 cubic miles, to account f volume of material removed by the slight genera sion of the constructional surface of the Tuscan mation, and for the volume of hidden Tuscan

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HE PLUTONIC AND METAMORPHIC ROCKS O THE BEN LOMOND MOUNTAIN AREA ANTA CRUZ COUNTY, CALIFORNIA*

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ABSTRACT

Ben Lomond Mountain, which is situated in the California Coast Ranges northwest of Monterey Bay, is underlain by a complex of plutonic and metamorphic rocks. The crystalline core of Ben Lomond Mountain is an irregularly shaped, northwest-trending mass with an exposed area of about 40 square miles. It is surrounded by Tertiary sedimentary rocks generally in fault contact on the northeast and depositional contact on the southwest. The flat eroded top of the crystalline core dips gently seaward.

Plutonic rocks of the complex comprise several distinct intrusions with a compositional range from gabbro to adamellite. Field relations suggest two more or less separate periods of intrusion. The first period, synkinematic with deformation and high-grade regional metamorphism, resulted in the emplacement of stocks of gneissic granodiorite and adamellite/adamellite. Subsequent to this a plug of hornblende-cummingtonite gabbro was intruded, followed by a composite larger mass of quartz diorite (Ben Lomond pluton), both of which have imposed thermal metamorphism on the pre-existing rocks.

Analyses of gabbro, quartz diorite, and adamellite show good agreement with variation diagrams of well-established calc-alkaline rock series; field and laboratory evidence point to a magmatic origin for these units, with only minor metasomatism or granitization. An analysis of aplite shows an abnormally high content of K_2O, and this rock may reflect localized potash metasomatism, although it could also have been formed by differentiation under magmatic conditions.

Metamorphic rocks include pelitic schist, quartzite, marble, and local hornfels and granitic gneiss; they form roof pendants patches with a total area of about nine square miles. More or less pure calcite marble may be interbedded with schist, or may form isolated lenses up to one mile long. Calc-silicate rocks with little or no calcite are locally developed, notably near intrusive contacts. The principal metacarbonate minerals developed in marble are quartz, diopside, phlogopite, tremolite, clinopyroxene, and forsterite; less common are wollastonite, chondrodite, scapolite and garnet. Wollastonite occurs in only one locality near a granite contact, whereas elsewhere quartz and calcite coexist stably.

Pelitic schists commonly contain quartz, biotite, almandine garnet, and feldspars. Within a few hundred feet of plutonic contacts, cordierite, sillimanite and K-feldspar are locally developed, at least in part by replacement of micas and garnet. Such reactions are apparently related to the intrusion of the gabbro-quartz diorite sequence into pre-existing, regionally metamorphosed rocks. In terms of facies classification, the metamorphic mineral assemblages reflect conditions near the boundary between the almandine amphibolite and hornblende hornfels facies, with local near-contact assemblages indicative of the pyroxene hornfels facies.

Available evidence suggests that the crystalline complex at Ben Lomond Mountain may be equivalent to crystalline rocks of the Santa Lucia Range to the southeast. Potassium-argon age determinations of granitic rocks in the Coast Ranges indicate a Late Cretaceous age, generally contemporaneous with major intrusions in the Sierra Nevada and the Southern California batholith.

INTRODUCTION

Location and Accessibility. Ben Lomond Mountain, located in the westernmost part of the California Coast Ranges north of Monterey Bay, forms an elongated ridge trending northwest between the city of Santa Cruz and Big Basin State Park; it is bounded on the northeast by San Lorenzo River and on the southwest by the Pacific Ocean, and lies entirely within the Ben Lomond, California, 15-minute quadrangle.

The crest of Ben Lomond Mountain forms a relatively flat ridge with a maximum elevation of 2,650 feet. The flanks of the mountain are steep, in some places precipitous, especially on the upfaulted northeastern side. The region is deeply dissected by streams: those northeast of the divide form tributaries to San

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Lorenzo River, whereas those southwest of the divide flow into the Pacific Ocean. The principal stream on the northwest side of the ridge is Fall Creek; on the southwest side, the most important ones are Scott Creek and its tributaries, and San Vicente, Laguna, and Majors Creeks. Stream canyons are generally steep with V-shaped walls, and in general afford the best exposure of fresh rock.

The area is accessible by a number of paved and secondary roads, chief among which are State Highway 9, running approximately parallel to San Lorenzo River between Santa Cruz and the town of Boulder Creek; and Empire Grade, which follows the crest of the mountain from Santa Cruz to the fire lookout at Eagle Rock. Pine Flat Road and Smith Grade trend across the mountain west of Empire Grade, and several rather steep grades connect Empire Grade with State Highway 9. A number of unpaved roads and trails, many of them private, provide further access.

Most of the northern portion of Ben Lomond Mountain is covered by heavy forest, whereas southeastern areas, within a few miles of Santa Cruz, are characterized by grassy slopes. In addition, much of the area, particularly those portions burned off about 20 years ago, is covered by dense, virtually impenetrable underbrush.

The dense vegetation, together with the deep weathering and resulting limited outcrops, make precise mapping difficult in many places; consequently, most of the contacts on the geologic map (Map 1) are approximate.

Previous Work. The area covered by this report was first described by Branner, Newsom, and Arnold (1909). A short description of the crystalline rocks was given by Fitch (1931), and a structural and geomorphological treatment by Rode (1930). Spotts (1962) made a study of the accessory minerals in several of the Coast Ranges plutons, including those of Ben Lomond Mountain. The sedimentary rocks in the region have been described by Cummings, Touring, and Brabb (1962), and in several unpublished theses and student reports from Stanford University (Burford, 1961; Sisler, 1960; J. C. Clark, unpublished).

The present paper is based on a Ph.D. dissertation presented to Stanford University (Leo, 1961). Field work was begun in 1952 and occupied a total period of about 6 months. Mapping was done on aerial photographs on a scale of 1:20,000, and on 7½-minute topographic sheets when these became available. Selected locality and sample numbers pertinent to the discussion are indicated on the geologic map (Map 1), and are the same as those used in the original dissertation. The prefix SC as used throughout the text refers to sample numbers; localities corresponding to samples have the same number without the prefix.

Acknowledgements. The work at Stanford was done under the guidance of Professors C. O. Hutton and Robert R. Compton. It is a pleasure to express my sincere appreciation to these individuals, as well as to other members of the faculty staff for frequent advice and cooperation. I am also grateful to the School of Earth Sciences, Stanford University, for various scholarships and other financial aid.

The present paper has benefited greatly from c nical reviews by Robert R. Compton, Robert G. O man of the U. S. Geological Survey, and by geo of the California Division of Mines and Geolo

Regional Context and Age Relations. The Be mond massif is one of a series of crystalline com exposed along the California coast from Bodega e southeast to La Panza Range, including Point Ar Farallon Islands, Montara Mountain, Santa Lucia In and Gabilan Range (fig. 1). Granitic rocks no Ben Lomond Mountain are predominantly qu diorite (cf. Spotts, 1962, p. 1226); between Tom Bay and Point Reyes considerable granodiorite an adamellite are observed, while at Ben Lomond Mou tain distinct intrusions of gabbro, granodiorite an granite adamellite are associated with a much g quartz diorite body. High-grade (predominantly am phibolite facies) metasedimentary rocks at Ben Lo mond Mountain, including pelitic schist, hor quartzite, and marble, are thought to correspo Trask's Sur series of Santa Lucia Range (Trask, 1 Such rocks constitute about one-fourth of the ou area on Ben Lomond Mountain, but are scarce ab sent in exposures of the granitic basement to the n

The crystalline rocks of the Coast Ranges ar in tributed along a northwest trending belt, called Sa linia" by Reed (1933, p. 31). More recently, thi has been recognized as a tectonic block with a cr line basement, about 40 miles wide and at leas miles long, between the San Andreas and Nacim fault systems (fig. 1). Through repeated u which may be continuing to the present day, the di mentary cover has been partly stripped off to e the crystalline basement.

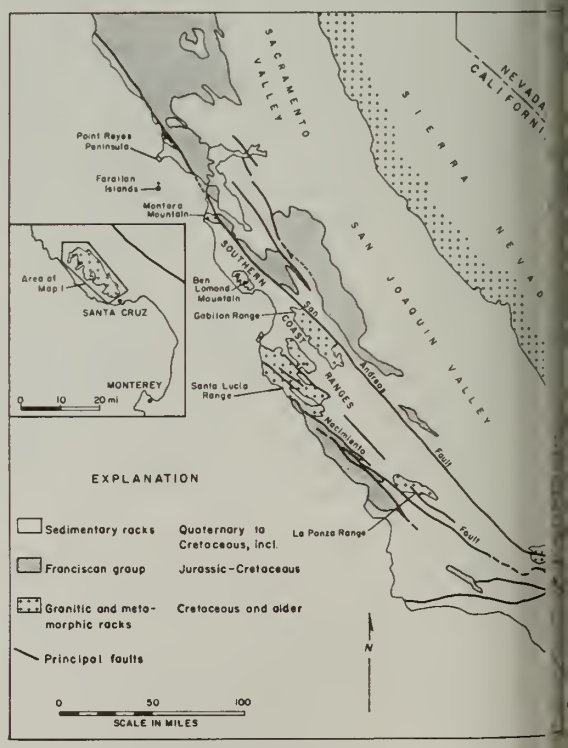


Figure 1. Map showing location of Ben Lomond Mountain and cr crystalline complexes in the Coast Ranges of California.

San Andreas-Nacimiento block is devoid of
n scan rocks, a fact which has been regarded as
d ce for extensive movement related to the San
d as fault. The oldest sedimentary rocks within
lock are late Upper Cretaceous miogeosynclinal
k of the Great Valley sequence (Bailey and others,
4 Sedimentary formations surrounding the crys-
in core of Ben Lomond Mountain range from
e ene to late Miocene (Cummings, Touring, and
b 1962; J. C. Clark, unpublished). Contacts be-
e crystalline rocks and younger sediments are
t faulted and partly depositional.

T considerable similarities, both in lithology and
r metamorphic grade, that exist between rocks
t Ben Lomond area and those of the Sur series
elated intrusions of Santa Lucia Range clearly
i e that the rocks in the two areas are the prod-
t the same general orogenic episode. Investiga-
s in Santa Lucia Range (Compton, 1960, and
6 as well as this study, suggest that the Santa
i rocks may represent a deeper level of plutonic
w than that which is reflected in the Ben Lo-
n area and north. Available K-Ar age determina-
s of Coast Range granitic rocks between Point
r e and Big Sur (Curtis, Evernden, and Lipson,
8 Zeller, 1965) fall into the range of 71.0–91.6
. corresponding to Late Cretaceous, and are cor-
t with the Santa Lucian orogeny (Taliaferro,
3 p. 130–132; Curtis and others, 1958).

a ometric age determinations on granitic rocks
n the central Sierra Nevada largely fall within
s ne general time span. Curtis and others (1958)
p K-Ar ages ranging from 76.9 to 95.3 m.y. for
c s in the Yosemite Valley region. In the Sierra
r a southeast of Yosemite, K-Ar ages on several
o plutons fall into the span of 80–90 m.y. (Kistler
hers, 1965).

e l-alpha ages from the Southern California bath-
h nd related rocks give a mean value of 110 ± 13
. Larsen and others, 1958). Although it is now
a nt that lead-alpha ages tend to be too great
t Armstrong, 1966, p. 586–589), regional geologic
l ce (Larsen, 1948) indicates an early Late Creta-
u ge for the batholith. Thus, granitic rocks from
C lifornia Coast Ranges, the central Sierra Nevada
e Southern California batholith appear to be
r imately contemporaneous.

s been suggested (e.g., Curtis and others, 1958)
, n early Late Cretaceous time, the present San
d s-Nacimiento block lay along a line which in-
l the present Sierra Nevada and Southern Cali-
i batholiths; and that subsequent to the Santa
i orogeny with accompanying granitic intru-
s right-lateral strike-slip movement of as much as
1 les along the San Andreas fault (Hill and Dib-
l 1953) resulted in the present distribution of
st line blocks. This hypothesis is discussed by
e and others (1964), who conclude that a com-
b n of strike-slip movement and lateral north-
w rd drift of a block bounded by the San An-
a ault may better account for some of the regional
t ships. According to this idea, emplacement of
e retaceous granitic rocks must have occurred well after separation of the southwestern block (Bailey et al., 1964, p. 162).

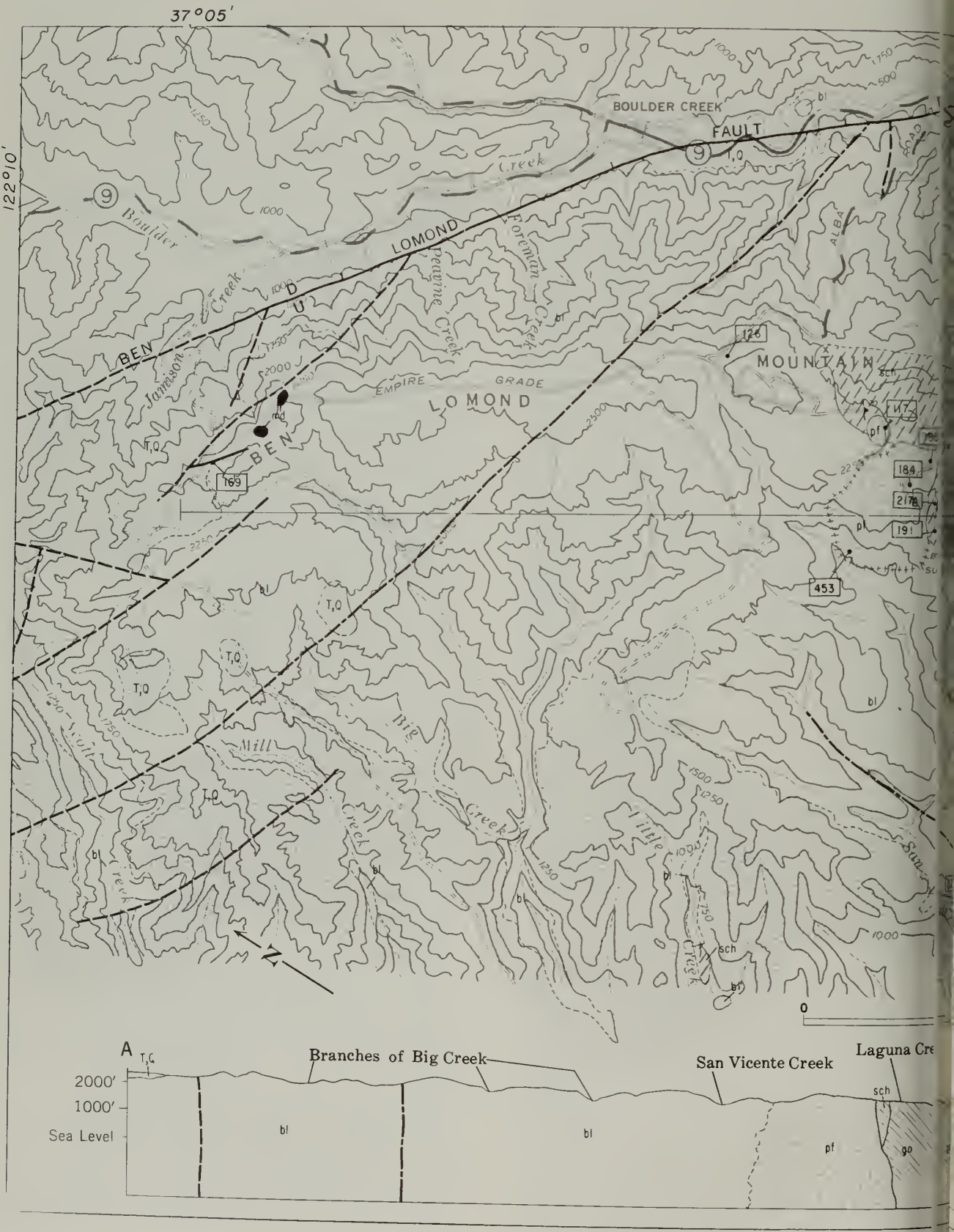
The Crystalline Complex at Ben Lomond Mountain. The crystalline complex at Ben Lomond Mountain comprises a diversified series of plutonic and metamorphic rocks. By far the largest single unit is a mass of medium-grained quartz diorite (Ben Lomond pluton), which extends from just south of the fire lookout station at Eagle Rock to within 1 mile of the city limits of Santa Cruz. The northeastern margin of the pluton, bounded by the Ben Lomond fault, rises abruptly from the valley of San Lorenzo River; the southwestern boundary is lobate and irregular, reflecting a gentle southwest dip of the unconformity over the pluton. The next largest intrusive unit, a moderately coarse-grained leucocratic rock ranging in composition from granite to adamellite (Smith Grade pluton), forms an ellipsoidal mass west of the town of Felton. Two small, but quite distinct and probably unrelated masses of granodiorite occur on Laguna Creek near the center of the complex and near Wilder Creek just north of Santa Cruz. From a mineralogical and genetic point of view, the most unusual intrusive rock is hornblende-cummingtonite gabbro that forms a plug along Pine Flat Road, as well as small sporadic masses in quartz diorite in other parts of the area.

Rocks described as granodiorite by Sisler (1960) and Burford (1961) crop out in stream bottoms in the Glenwood Basin area, some 10 miles east of Ben Lomond Mountain. These rocks are doubtless part of the crystalline complex, although their relation to any specific intrusive unit is a matter of conjecture.

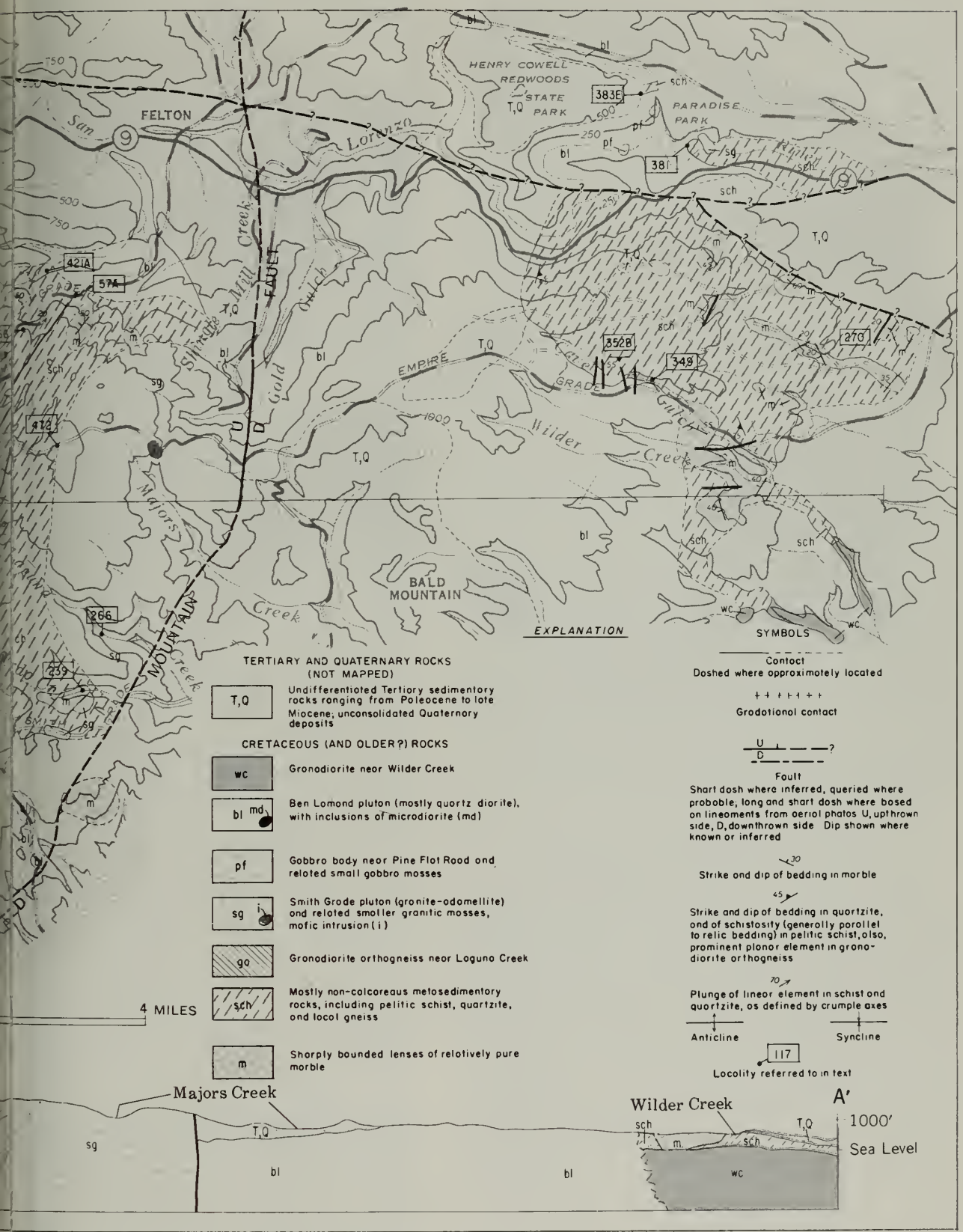
Metamorphic rocks are confined to the southern part of the complex, where they form several major lenses. These rocks are all of metasedimentary origin, and comprise marbles, quartzites, and pelitic schists; the last are locally, and very moderately, migmatized. Except for local calcareous hornfelses, the metasedimentary rocks are generally rather coarse-grained. Pelitic types are characterized by almandine and sillimanite; calcareous rocks exhibit a diversified assemblage of minerals, among which wollastonite-bearing ones (at an intrusive contact) probably reflect the highest grade of metamorphism.

Structural and petrographic evidence suggests that the plutonic rocks of the complex do not form a simple differentiation sequence, but may reflect at least two periods of intrusion and metamorphism. An initial period of regional metamorphism at amphibolite facies grade was accompanied by synkinematic intrusion of the Smith Grade and Laguna Creek plutons, which were deformed with the metasedimentary rocks. The gabbro body near Pine Flat Road and Ben Lomond pluton appear to be younger, and have imposed marginal contact metamorphism on regional assemblages.

In subsequent sections, the plutonic rocks are described in order of their apparent relative ages, followed by the metamorphic rocks. The gabbro body near Pine Flat Road, because of its unusual mineralogical and textural features, has been discussed in somewhat greater detail than the remaining plutonic rocks.



Map 1. Geologic map of the plutonic



Mountain area, Santa Cruz County, California.

Faulting of the Ben Lomond Block. Considered as a structural unit, the Ben Lomond Mountain fault block has been tilted southwestward along the compound Ben Lomond fault (see also the San Francisco Sheet of the Geologic Map of California, 1961). This fault, believed to dip steeply northeast and to have a vertical displacement of 3,000 to 10,000 feet (Cummings, Touring, and Brabb, 1962, p. 215), is one of a series of northwest-striking normal faults in the region. The Ben Lomond fault cuts both quartz diorite and adjacent Tertiary sedimentary rocks; the youngest rocks known to be cut by it belong to the Monterey Formation of Miocene age. The fault is well exposed in several stream canyons northwest of the town of Boulder Creek. Subsidiary faults along the northern margin of the Ben Lomond pluton contribute to an angular outline.

Another major fault, which constitutes the southern limit of the raised block, trends roughly east-west near Bald Mountain, passes through Felton quarry, and apparently continues northeast along Shingle Mill Creek and Bean Creek. This fault, here referred to informally as Bald Mountain fault, truncates the Smith Grade pluton and brings it against a portion of the Ben Lomond pluton to the south. Movement on the Bald Mountain fault has apparently been downward to the south, but the amount of displacement is not known, nor is the relation known between the Bald Mountain and Ben Lomond faults.

Other faults shown on Map 1 are somewhat conjectural, and were determined with the aid of aerial photos on the basis of topography, outcrop patterns, and persistent lineations, rather than by direct observation. Faults in this category include the one trending northwest across the mountain along Clear Creek and the fault trending northward along the western branch of San Vicente Creek. A fault trending from Henry Cowell Redwoods State Park toward Santa Cruz west of San Lorenzo River, with a south-trending branch south of Paradise Park, very likely represents the continuation of Ben Lomond fault.

PLUTONIC ROCKS

Granodiorite Orthogneiss Near Laguna Creek

Isolated masses of relatively homogeneous gneiss crop out near the crest of Ben Lomond Mountain. The largest mass, measuring about 1 mile in length and half a mile across, is located west of Empire Grade between Ice Cream Grade and Pine Flat Road, and is well exposed along Laguna Creek and its tributaries. Another exposure of the gneiss is located just west of Skyline Ranch on the flat crest of the mountain, and a third on a tributary to Fall Creek east of the crest. These three exposures very probably reflect a single gneiss mass at depth. Study of this rock type was principally confined to the exposures near Laguna Creek.

The granodiorite orthogneiss is a medium-grained leucocratic, and rather uniformly textured rock, which is everywhere bounded by quartzite and pelitic schist. Contacts along Laguna Creek and its tributaries, where exposed, appear sharp and locally discordant, with intense crumpling of adjacent metamorphic rocks. The gneissic appearance of the r diorite gneiss derives from a prominent plana tu ture, defined by mafic minerals concentrated a narrowly spaced, subparallel planes, with a fair c sistent northeast strike and southeast dip. Awa fr crumpled contacts, attitudes in adjacent sch quartzite generally parallel those in the granio orthogneiss. Along Pine Flat Road near the o Doon substation (loc. 191), orthogneiss rests on along a subhorizontal contact, although foliati schistosity, respectively, of the two rock type tinue essentially parallel, with a northeast stri southeast dip. Although the limited exposures no definite conclusion, these relationships sugge kinematic intrusion of the granodiorite into a metasedimentary rocks.

The principal minerals in the gneiss are K-feldspar, and plagioclase, in proportions sponding to granodiorite (fig. 2). For this reas also because the uniform nature and structura tions of the rock strongly suggest a magmatic than a sedimentary origin, the rock is termed a diorite orthogneiss.

Mafic minerals include red-brown biotite and re hornblende, concentrated in bands 1–5 mm apa T direction of these bands is emphasized by subp shear planes along which quartz and feldspa ha been crushed and rehealed. Ubiquitous replacem plagioclase by quartz and K-feldspar suggest r b zation and redistribution of a low-melting eutectic.

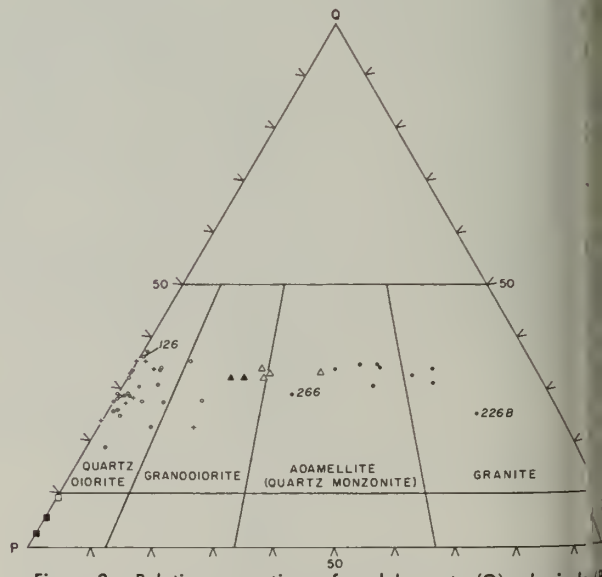


Figure 2. Relative proportions of modol quartz (Q), plogiocl and potossium feldspor (K) in granitic rocks from Ben Lomond toin. (○) = Ben Lomond pluton north of the Bald Mountoin (+) = Ben Lomond pluton south of the Bold Mountain fault; large microdiorite inclusion, and (■) = small autolithic inclusi Ben Lomond pluton; (▲) = gronodiorite orthogneiss neor Creek; (△) = granodiorite near Wilder Creek; (●) = Smith pluton, reloted plugs, and an aplite dike (SC 226B). Numbered refer to onalyzed rocks (see Toble 1). (Classification modified Johannsen, 1939, p. 144.)

regular, microscopic quartz-feldspar bands that all traverse the rock may represent the palingenic melt squeezed into joints and fractures. This age for shearing and mobilization is consistent with the hypothesis of synkinematic emplacement of gneiss.

Smith Grade Pluton

The Smith Grade pluton is a mass of granitic rock, varying in composition from adamellite to granite, exposed along Empire and Smith Grades, in Felton quarry, and along Majors and Laguna Creeks. The rock, which was not distinguished from quartz diorite in early mapping (Branner et al., 1909), is roughly elliptical in outline and covers an area of about three square miles. Small outliers are located along Smith Grade west of the main mass. Isolated adamellite bodies which may or may not be related to the Smith Grade intrusion, crop out along Felton-Empire Grade (loc. 5), near Paradise Park, and along Wilder Creek (location not shown on map).

The Smith Grade pluton has clear intrusive contacts against pelitic schist on Empire Grade. The fault contact between the Smith Grade pluton and the southern extension of the Ben Lomond pluton is exposed on Empire Grade and the road on the south bank of Gold Gulch.

J. Compton (written communication, 1965) has observed distinct lineations of biotite (the most prominent mafic mineral) in the pluton, with a strike from N 30° W to N 70° E; these lineations are generally parallel both to fold axes and mineral lineations in metamorphic rocks to the north and southeast of the pluton. This suggests that intrusion of the Smith Grade pluton was synkinematic with regional metamorphism, and possibly related in time to the intrusion of the Laguna Creek granodiorite orthogneiss.

The Smith Grade pluton consists of medium- to coarse-grained granitic rock with a pinkish to gray color on fresh surfaces and rusty-brown limonite coatings on the well-developed joint planes. Biotite and dark garnets are the most evident mafic constituents. The granite is characteristically altered, with widespread chloritization of biotite and local development of pyrite. In some places, as in road cuts along Empire Grade, altered granite may grade sharply outward into fresh rock and reflects normal weathering. Elsewhere, notably in Felton quarry, alteration is much deeper and may reflect hydrothermal activity. The alteration is particularly intense along a conspicuous shear zone in Felton quarry which may be related to the Old Mountain fault. In its exposures west of Empire Grade, the Smith Grade pluton appears to be deeply altered. The adamellite plug on Felton-Empire Grade (loc. 66) is extremely fresh, and shows sharp intrusive contacts against biotite schist.

In thin section the rock appears hypidiomorphic to allotriomorphic. The texture is markedly irregular, with a range in grain size of 0.1 mm to 1 cm. Plagioclase has a maximum compositional range of An_0–An_{33}, but the common range is about An_{5-18}. It tends to form clusters of subhedral grains with cloudy cores and albitic rims, whereas quartz and K-feldspar occur as irregular interstitial patches. Relative proportions of quartz and feldspar indicate compositions ranging from adamellite to granite.

The main accessory minerals, which generally do not total more than 5 percent, include red-brown biotite, almandine-spessartite garnet, muscovite, and pyrite. Other accessories reported by Spotts (1958, p. 28, 73) include monazite, xenotime, and zircon. A chemical analysis of adamellite from the Smith Grade pluton is listed in Table 1.

Mafic Inclusions. Several large mafic bodies up to 500 feet across are exposed within the Smith Grade pluton along Empire Grade. A fresh specimen of one of these has a granoblastic texture and consists of plagioclase (An_{50-52}), hornblende, biotite, and quartz. Mostly these bodies are deeply weathered but display distinct, though irregular, textural variation between fine- and coarse-grained mafic rock, locally traversed by granite pegmatite. These masses probably represent dikes or small plugs. Smaller, slightly altered inclusions of pelitic schist near the northern contact of the pluton are clearly derived from the large schist body to the north.

Gabbro Body Near Pine Flat Road

A mass of gabbro consisting dominantly of hornblende and calcic plagioclase crops out between San Vicente Creek and Empire Grade in the vicinity of Pine Flat Road, and is here referred to as the gabbro body near Pine Flat Road. The mass has a roughly circular outline and covers an area of about half a square mile. Smaller gabbro masses, each no more than a few hundred feet across, were noted about 1 mile northeast of San Lorenzo Valley School; and north of Paradise Park on San Lorenzo River and one of its tributaries. Most of the following observations refer to the body on Pine Flat Road.

The Pine Flat gabbro body is exposed in a few cuts along Pine Flat Road, along tributaries to San Vicente Creek, and in sporadic outcrops in the adjacent woods. The gabbro characteristically forms bouldery to massive outcrops with brownish-red weathered surfaces. The fresh rock is extremely hard and tough, and varies in color from greenish gray to black.

A distinctive structure in the gabbro, displayed in a cut along Pine Flat Road (loc. 184), is an abrupt and irregular alternation between fine- and medium-grained rock. The latter is the more abundant phase, and effectively forms the matrix for dark, finer grained fragments, a few inches to several feet across, that may be rounded, angular, sub-tabular, or completely irregular. The limited exposures make it difficult to obtain a clear impression of the abundance and distribution of the finer grained fragments, but they seem to be ubiquitous throughout the gabbro, and are always mineralogically identical to the enclosing coarser-grained phase. Contacts between the two phases are always sharp, and even in thin section no transitional zone is apparent (photo 6).

In isolated localities, as along a tributary to San Vicente Creek (loc. 453), the gabbro has a distinctly banded aspect, finer and coarser grained rocks form-

ing sharply bounded layers a few inches to a few feet thick. Exposures of clear-cut layering are too restricted to be called characteristic of the gabbro, and the relation, if any, between layering and brecciation, is not clear.

A possible explanation of the brecciated structure is that the fine-grained rock represents an early injection of relatively dry gabbro magma. After partial or complete solidification, this was invaded by a second, more volatile-rich magma that crystallized as coarser grained, but otherwise similar, rock. Such a mechanism was proposed by Miller (1938) to explain strikingly similar structural relations in the San Marcos Gabbro of southern California. Alternately, the brecciation could have been produced by marginal cataclasis of an originally layered gabbro. Neither hypothesis can be definitely established on the basis of available data.

The contact between gabbro and quartz diorite to the north and west appears to be gradational through a zone of progressively less calcic plagioclase and increasing content of quartz and biotite toward the quartz diorite contact. Contacts with metasedimentary rocks south and east of the gabbro body, where exposed, are fairly sharp and evidently intrusive.

The principal minerals in the gabbro are intermediate to calcic plagioclase with a maximum compositional range of An_{39-94}, green-brown hornblende, cummingtonite, and biotite; hypersthene is rare, but constitutes 10 percent of one of the few rocks in which it occurs. Accessories include quartz, ilmenite, apatite, sphene and rutile. The last two minerals are especially abundant in specimens from the eastern margin of the mass, where sphene forms euhedral prisms up to 4mm long, and rutile is enclosed in irregular patches of secondary sphene. High titanium content of these rocks is further suggested by the pale to dark brown color of hornblende, (Deer, 1938, p. 73–74) and by platelets of rutile (?) exsolved along hornblende cleavage planes.

The major minerals, especially in the coarser-grained phase, display distinctive and revealing textures. Hornblende and plagioclase tend to be segregated into clusters and clots of grains, which define a rude banding on a megascopic scale. Individual hornblende grains have a highly irregular and shredded appearance, and tend to penetrate along borders of adjacent plagioclase grains; locally a true sieve texture is developed. This relationship suggests late growth of hornblende at the expense of plagioclase. Hornblende adjacent to plagioclase boundaries is commonly pale green to blue green, and may be more actinolitic than the brown hornblende in the interior of plates. Colorless cummingtonite forms irregular but sharply bounded patches within hornblende plates; alternately, it may occur as fibrous, radiating aggregates (photo 7).

Plagioclase occurs in clusters of anhedral grains that commonly show evidence of crushing and rehealing. A characteristic texture is a "mottling" effect caused by abrupt, spotty, and random variations between more sodic and more calcic compositions within a single grain (photo 7). Calcic islands may have compositions of bytownite or even anorthite, while the remainder of the grain is usually andesine-labradorite. This texture is attributed to differential mig... Ca^{+2} and Al^{+3} from plagioclase, which has ... contributed to development of hornblende; c... ant inward migration of Na^{+} and Si^{+4} must be ... Such migration is regarded as a process of r... phic, rather than magmatic, differentiation. Be... mottled texture, some plagioclase shows norm... ing, and most of it exhibits complex twinnin... features clearly magmatic.

Twin lamellae are continuous without offset ... adjacent sodic and calcic portions of mottle... indicating that such grains have undergone ... tial compositional changes while maintaini... original form. Locally throughout the Pine Fl... and also in gabbro from smaller masses near Fa... and near Paradise Park, abrupt but normal z... plagioclase greatly predominates over the o... texture. The overall aspect of these latter ... moreover, is subophitic and relatively homoge... compared to the banded and segregated textu... acteristic of the Pine Flat body.

Fine-grained gabbro differs from the coarser ... type chiefly in that the texture is more regul... equant, smoothly bounded plagioclase grains an... stitial, anhedral grains of hornblende and/or eu... tonite. Plagioclase is only slightly zoned, and ... displays the mottling so characteristic of the ... phase. This texture is granoblastic, and proba... flects metamorphic recrystallization. Transiti... tween the finer and coarser rock are sharp, ... mineralogical differences are discernible (phot...

Hypersthene-bearing gabbro occurs spor... within the Pine Flat body and in the Paradise ... calities, and its relation to hypersthene-free type... clear. Hypersthene may constitute up to 10 ... of the rock, and is rimmed either by cummin... or by hornblende in obvious reaction relation; ... case, cummingtonite forms a rim between hype... and hornblende. No hypersthene relics were ol... in normal hornblende-cummingtonite gabbro, al... it appears quite probable that original hyperst... the source of much, if not all, of the cumming...

Petrogenesis. An analysis of hornblende ... from Pine Flat Road is listed in Table 1. The co... tion is closely comparable to hornblende gabbr... the San Marcos Gabbro (Miller, 1937), and to a ... hornblende gabbro (Nockolds, 1954). The posi... the analysis on variation diagrams (fig. 3) is c... ible with a calc-alkalic differentiation sequence.

The abundance of amphiboles and relative s... of pyroxenes indicate a water-rich environm... crystallization, in which original pyroxenes (a... vine?) were converted to amphiboles in re... which probably also involved plagioclase. ... (1942) has described development of poikilitic ... blende from plagioclase in the Cortlandt Comp... New York. In the gabbroic complex of Belhe... Aberdeenshire, Stewart (1946) has traced the ... opment of fibrous cummingtonite from olivin... orthopyroxene through the action of late-stage ... matic liquids rich in water and silica. A basic re... in the gabbro body near Pine Flat Road may b... resented schematically as follows:

...gite + 11 hypersthene + plagioclase + water → hornblende + cummingtonite

...mingtonite could be formed directly from hy-...e or olivine by the addition of water and ...f. Stewart, 1946, p. 483–484):

...ersthene + water + silica → cummingtonite
...ne + 2 water + 9 silica → 2 cummingtonite

...a, as stated previously, no evidence of original ...was detected in the gabbro, and no olivine is ...orm.

...escribed mineral reactions in the gabbro body ...ably not to be attributed solely to late-mag-...ocesses; rather, they may well be related to ...ution and recrystallization under metamorphic ...ns. A metamorphic stage following original ...zation is indicated by the peculiar clotted tex-... the coarser gabbro; development of mottling ...oclase; late growth of amphiboles; and the ...c aspect of the finer grained rock. The rude ... the shredded aspect of hornblende patches, ... crushed and rehealed nature of plagioclase ... moreover, all are indicative of shearing dur-...stage of recrystallization. As previously noted, ..., plagioclase grains which exhibit complex ... and normal zoning have not been completely ...llized, but more probably represent relics of ...c crystallization. In view of the general ab-... low-grade minerals expected from the break-... calcic plagioclase, especially epidote and sodic ...se, it is concluded that recrystallization of the ...ook place at high temperature, and was essen-...ontinuation of the magmatic phase. Most prob-...e necessary heat for sustained recrystallization ...plied by the emplacement of the Ben Lomond ...which was intruded against the nearly crystal-...t still hot gabbro masses. Mineralogical and ...reconstitution took place under the prolonged ... and shearing stress accompanying the intru-... the quartz diorite. In certain areas where di-...tress was small or negligible, gabbro textures ...essentially magmatic, although conversion of ...e (and olivine?) to amphibole proceeded as ...out the rest of the gabbro.

...pertinent to point out certain similarities and ...ces between the Pine Flat gabbro body and ...kitic rocks in Santa Lucia Range described ...pton (1960). In the latter locality, original ... has been converted to charnockitic rocks by ...le-facies metamorphism closely related to, and ... continuous with, emplacement of the tonalite. ...arnockitic rocks are granoblastic and thor-...recrystallized; adjacent metasedimentary rocks ...ur Series of Trask (1926), originally of am-...le grade, have been discontinuously converted ...lite facies assemblages under relatively local-...conditions of high temperature and, apparently, ...y low fluid pressure.

...ugh the two situations differ considerably in ...f field relations as well as the rock types in-...the comparison is pertinent in two ways. First, ...uations involve metamorphism, closely related in time to their emplacement, of fairly small plutons separated by some 70 miles along the same orogenic belt. Second, the Pine Flat gabbro body represents amphibolite facies grade (with adjacent calcareous hornfelses of pyroxene hornfels facies). Except for such local contact aureoles, Ben Lomond metamorphic rocks generally reflect amphibolite facies metamorphism, and granulite facies rocks have not been found in the area. It may be inferred from this that, at least locally, plutonic temperatures were higher in the core of Santa Lucia Range than in the Ben Lomond Mountain area, which suggests that at least some rocks presently exposed in Santa Lucia Range represent a deeper level in the crust than those of Ben Lomond Mountain.

Ben Lomond Pluton

The major intrusive unit of the crystalline complex at Ben Lomond Mountain, here named Ben Lomond pluton, is a mass which consists dominantly of quartz diorite, and covers an estimated 25–30 square miles, or about three-fourths of the surface area of the entire complex. The unit occurs in two distinct areas, to the north and south of Bald Mountain fault. As displacement of this fault is apparently downward on the south, the southern quartz diorite exposure should represent a higher horizon in the pluton. The actual net displacement is unknown.

Rocks in contact with the Ben Lomond pluton include the metamorphic series, the gabbro body near Pine Flat Road, the Smith Grade pluton, and Tertiary sedimentary rocks. The Ben Lomond pluton has intruded the metamorphic rocks and caused local contact metamorphic effects. The contact with the Pine Flat gabbro body is also intrusive and partly gradational, with the metamorphic effects described in the preceding section. The contact with the Smith Grade pluton is the Bald Mountain fault. The Tertiary sedimentary rocks are in simple depositional contact with the Ben Lomond pluton throughout its southern and southwest exposures. Along the northeastern and northern border, contacts between quartz diorite and sandstone may be depositional (as on Clear Creek) or faulted (as on Peavine Creek), or a combination between the two (as at the northern contact of the pluton on Empire Grade, loc. 169; photo 1).

Structures within the quartz diorite include a number of prominent but rather randomly oriented joint planes, and localized and discontinuous lineation defined by oriented mafic minerals and elongated mafic inclusions.

No prominent linear or planar structures were noted comparable to those of the granodiorite orthogneiss near Laguna Creek or the Smith Grade pluton. This fact is regarded as evidence that the Ben Lomond pluton is not synkinematic relative to the regional metamorphism, but may belong to a later, and possibly quite distinct, intrusive phase which was initiated by intrusion of the Pine Flat gabbro body.

Minor rock types that occur within the Ben Lomond pluton include two distinct types of mafic inclusions (described below), dikes of diorite, aplite, and pegmatite, adamellite plugs, and sporadic masses of leucocratic quartz diorite with 40 percent quartz.

Photo 1. Depositional contact, modified by faulting, between quartz diorite (left) and Butano Sandstone (Eocene). Empire Grade at northern boundary of Ben Lomond pluton, 0.1 mile southeast of Jamison Road intersection (loc. 169).

The quartz diorite is a medium-grained, granitic rock with a light gray color on fresh surfaces and conspicuous hornblende and biotite. The texture is hypidiomorphic granular. The principal minerals with ranges in their percentages (based on 35 modal analyses) are as follows: plagioclase (An_{28-55}), 47–64; quartz, 16–31; K-feldspar, nil to 12 (average 2.5); hornblende plus biotite, 7 to 28; and accessory sphene, epidote, magnetite zircon, and apatite, and tourmaline.[1] Variation in relative proportions of quartz and feldspar are shown in figure 2. Both hornblende and biotite tend to have a brownish green shade in the northern part of the pluton, and a red-brown shade in the portion south of the Bald Mountain fault. This difference may be related to a higher Fe^{+3}/Fe^{+2} ratio in these minerals in the southern quartz diorite relative to the northern. Semi-quantitative spectrographic analyses of hornblende and biotite from quartz diorite in the two areas show no appreciable difference in Ti and other minor and trace elements.

Several modal parameters including color index, hornblende-biotite ratio, and K-feldspar content were plotted on an outline map of the pluton in an attempt to discover systematic variations in composition. Variations in these parameters, however, were found to be quite random. This randomness, insofar as it is not caused by sampling error, seems to reflect a real heterogeneity in the quartz diorite, which is further borne out by irregularly distributed mafic inclusions

[1] Spotts (1958) reports the following additional accessory minerals: allanite, ilmenite, anatase, gahnite, garnet, hypersthene, monazite, salite, rutile, pyrite, pyrrhotite, sphalerite, and zoisite.

with a wide range of shapes and sizes, and loc e cratic masses with a much lower mafic mineral n than normal quartz diorite. Both of these feat s gest contamination of the pluton, whether by rock or by associated, predominantly mafic, n rocks.

Mafic Inclusions. Mafic inclusions of two t e associated with the Ben Lomond pluton. Sma e soidal or elongate inclusions usually less thar long are sporadically distributed throughout th ern part of the pluton, but are rare in its south p These inclusions differ from the enclosing qua rite chiefly in the relatively greater concentr mafic minerals, absence of K-feldspar, and mo plagioclase (up to An_{73} in cores), and a tende y ward porphyroblastic texture. They are rega d autoliths of an early basic phase of the quartz o presumably related to gabbro similar to that f Pine Flat gabbro body.

Inclusions of a second type appear to be re to the northernmost part of the pluton, whe form irregular, generally angular masses up to across (photo 2). Two of these are situate

Photo 2. Large inclusion of microdiorite (entire field of vi by wedge of quartz diorite in Ben Lomond pluton. Note hamn center) for scale. Empire Grade, 0.8 mile southeast of Jamis intersection.

Empire Grade about half a mile southeast of th son road intersection, and their close proximity the road suggests that many more may rema detected in this general area. They are fine g and brittle, with a composition correspondin erally to diorite, and textures that range from granular to poikilitic. Locally such inclusions ap swarms of closely spaced skialiths within quart rite, apparently the result of fracturing and as tion of original larger fragments. These inc probably represent remnants of mafic dikes and intruded into quartz diorite when the latter was solidified. Several undisturbed dark dikes, pet cally similar to the inclusions, near the norther gin of the pluton indicate that emplacement of bodies continued after the quartz diorite magn completely solidified.

Granodiorite Near Wilder Creek

trusive body of unknown dimensions, corre-
g in composition to granodiorite, crops out in
Creek and Peasley Gulch about 1 mile north
Highway 1. Modal analyses of three speci-
ll close together in the granodiorite field, while
n corresponds to adamellite (fig. 2).

ock is light gray and generally fine to medium
with normally zoned oligoclase (An_{18-32}), and
wn biotite as the only varietal mineral. Acces-
clude monazite, sphene, apatite, and scattered
the last can occasionally be seen in outcrop.
ture is seriate and allotriomorphic; bands of
quartz and feldspar winding between shattered
phenocrysts suggest late protoclasis.

relative age of the granodiorite near Wilder
annot be definitely established. The rock is cut
erous dikes, and at least one plug, of garnet-
adamellite similar to the Smith Grade type,
s not known whether the latter are in fact
o the Smith Grade pluton. An alternate possi-
that the granodiorite represents a late border
the Ben Lomond pluton, which was intruded
i-crystalline mush, and thus acquired its proto-
tructure. The isolated exposures of granodio-
he Laurel quadrangle (Sisler, 1960; Burford,
ay bear a similar relationship to the Ben Lo-
luton.

Aplite and Pegmatite Dikes

and pegmatite dikes are widely distributed
Lomond Mountain, but are too small and dis-
us to be shown on the map (Map 1). They
igneous and metamorphic rocks, but are most
t near the northern border of the Ben Lo-
luton (photo 3). Aplite dikes, up to 20 feet
re generally tabular and sharply bounded
he host rock, with no appreciable chill zone.
nally they form composite dikes with dark,
rock (photo 4).

Aplite ond pegmotite dikes in Ben Lomond pluton cutting
ite; Empire Grode, about 200 feet southeost of loc. 169.
wer right) for scole.

Photo 4. Composite pegmotite-microdiorite dike cutting quortz dio-rite of Ben Lomond pluton; Empire Grode, holf o mile northwest of Camp Ben Lomond.

Coarse-grained pegmatites are less abundant than aplites, and are never more than a few feet across. The only minerals noted in either type of dike are quartz, feldspars, micas, and garnet (in aplite only). Pegmatite boulders containing dark tourmaline have been found in the bed of San Lorenzo River, but not in outcrop.

A chemical analysis (Table 1) of an apparently representative aplite, from a 15-foot dike along Laguna Creek (loc. 226B) is abnormally high in K_2O.

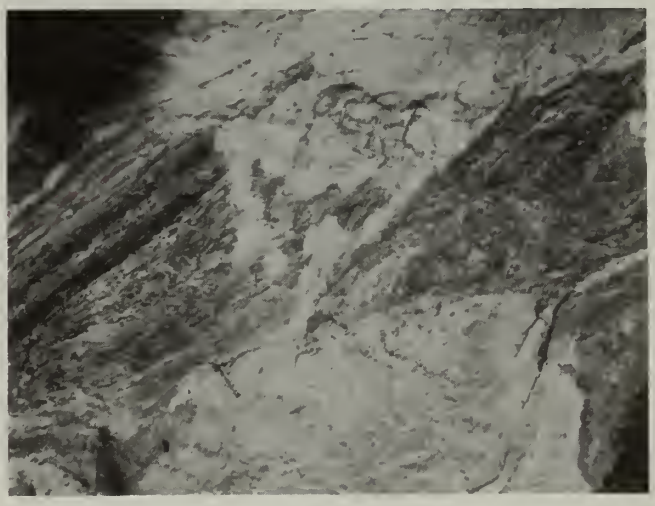


Photo 5. Gronitic pods of Smith Grode pluton replocing schist; Empire Grode, 0.9 mile south of Felton-Empire Grode intersection.

Such enrichment in K_2O could represent a somewhat anomalous differentiation trend toward a potassium-rich magma, or alternately it could reflect localized K-metasomatism. Neither alternative can be ruled out on the basis of available evidence. However, in view of the small bulk volume of aplite dikes, this enrichment is probably a localized and relatively insignificant phenomenon in the context of the overall composition of the intrusive rocks of the Ben Lomond crystalline complex (see figs. 2 and 3).

Migmatitization and Granitization

Limited exposures of migmatitic gneiss occur in Cave Gulch east of Empire Grade and in Peasley Gulch east of the quartz diorite contact. Such rock typically comprises schistose bands consisting of quartz, plagioclase (An_{33}), and deep red-brown biotite that alternate with granitic bands with about 60 percent quartz, 30 percent sodic andesine, 5 percent K-feldspar, and 5 percent micas. Such migmatite was probably formed by metasomatism related to the quartz diorite intrusion, although this cannot be conclusively demonstrated on the basis of available exposures.

Well-exposed contacts between intrusions and metasedimentary rocks show only minor migmatization. Two examples are the contact of the Smith Grade pluton along Empire Grade 1 mile south of the Felton-Empire Grade intersection (loc. 472), and that of the adamellite plug on Felton-Empire Grade (loc. 66). Somewhat more extensive granitization is displayed 0.1 mile north of location 472, where schist over a distance of 50 feet has been replaced by granitic pods up to 10 feet across (photo 5).

Scattered quartzo-feldspathic lenses, well exposed in schist along Empire Grade north of the Felton-Empire Grade intersection, show clear structural evidence of injection.

Petrogenesis

Chemical analyses and norms of four intrusive rock types from Ben Lomond Mountain are listed in Table 1. Three of these represent major intrusive units; the fourth is the somewhat anomalous potassium-rich aplite.

Compositionally the rocks illustrate a calc-alkaline association, as can be shown by plotting them on Larsen variation diagrams together with major calc-alkaline rock suites (fig. 3). Continuous differentiation from (gabbro)-quartz diorite through to granite is not implied, however, inasmuch as it has been shown that at least two distinct intrusive sequences may have been involved: (1) granodiorite orthogneiss and granite/adamellite (the relationship between these two is not known), and (2) gabbro/quartz diorite. Spotts (1962), on the basis of zircon morphology studies, concluded that the Smith Grade pluton appears to be genetically distinct from quartz diorite of the Ben Lomond pluton and the gabbro body near Pine Flat Road. The Laguna Creek granodiorite orthogneiss was not included in Spotts' comparison.

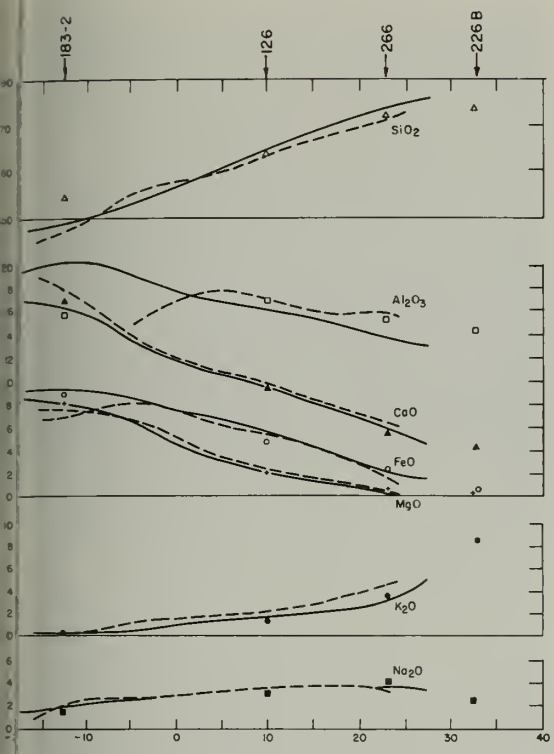
Evidence for Magmatic Origin. Most of the features of the Ben Lomond plutonic rocks point to a magmatic origin. The most convincing field evidence for this is the sharpness of contacts between plutons and metamorphic rocks, with local development of contact hornfelses, and only sporadic and localized migmatites. Not a single instance was noted of metasedimentary rocks grading into granitic ones through a migmatite zone. To put it another way, plutonic and metamorphic rocks are in general sufficiently distinct so that there is seldom any doubt concerning the nature of a given outcrop or specimen.

Table 1. Chemical analyses, norms and modes of int rocks from Ben Lomond Mountain.

	Sample 1	Sample 2	Sample 3	Sa
SiO_2	50.18	63.59	71.01	73
Al_2O_3	15.19	16.96	15.16	14
TiO_2	1.94	0.66	0.29	0
Fe_2O_3	0.75	0.97	0.23	0
FeO	7.84	4.04	2.24	0
MnO	0.15	0.08	0.07	0
MgO	7.93	2.32	0.56	0
CaO	12.50	5.74	1.70	0
Na_2O	1.49	3.34	4.18	2
K_2O	0.39	1.68	3.66	8
H_2O^+	1.42	0.49	0.60	0
H_2O^-	0.06	0.05	0.08	0
P_2O_5	0.03	0.14	0.11	0
	99.87	100.06	99.89	99
Norms				
Q	2.5	19.0	25.6	25
Or	2.5	10.0	22.0	48
Ab	13.5 } An_{72}	30.5 } An_{46}	38.0 } An_{16}	23
An	34.5	26.5	7.0	1
C	--	--	1.9	1
$CaSiO_3$	11.6	0.6	--	--
$MgSiO_3$	22.6	6.6	1.6	0
(Fe, Mn) SiO_3	9.2	4.4	2.8	0
Mt	0.7	1.1	0.3	0
Il	2.8	1.0	0.4	--
Ap	0.1	0.3	0.3	0
Modes (volume percent)				
Quartz	--	30.5	27.6	25
K-feldspar	--	0.4	26.9	60
Plagioclase	42.8 (An_{50-90})	52.0 (An_{42-50})	39.8 An_{5-18})	13 (A
Hornblende	53.3	3.7	--	--
Biotite	--	12.4	5.3	--
Muscovite	--	--	--	0
Chlorite	0.3	--	--	--
Sphene	1.0	0.3	--	--
Apatite	0.1	0.1	--	--
Epidote	--	0.5	--	--
Calcite	--	0.1	--	--
Garnet	--	--	0.4	0
Opaque minerals	2.5 (ilmenite)	--	--	--
Specific gravity	2.94 ± 0.02	2.77 ± 0.02	2.64 ± 0.01	2.57

Sample 1: Hornblende gabbro (SC 183-2), gabbro body near Road.
Sample 2: Quartz diorite (SC 126) from Ben Lomond plut Road, 800 feet southwest of Empire Grade.
Sample 3: Adamellite (SC 266) from Smith Grade pluton, Creek, about 500 yards north of sandstone-adamellite
Sample 4: Aplite (SC 226B) from 15-foot dike, Laguna Cre half a mile south of Ice Cream Grade.
Analyst: Doris Thaemlitz, University of Minnesota (1956).

Textures and internal structures of the vario tonic bodies are likewise compatible with more uncomplicated magmatic origin. This is especial of quartz diorite of the Ben Lomond pluton, v clear-cut hypidiomorphic granular textures. Th irregular textures of other granitic plutons are to processes such as protoclasis, shearing stress



re). Variation diogrom af Sauthern Californio batholith (solid ar racks of the Sierro Nevodo (doshed lines), with onolyses af mid Mountoin rocks superimpased. (After Larsen, 1948, p. 144,

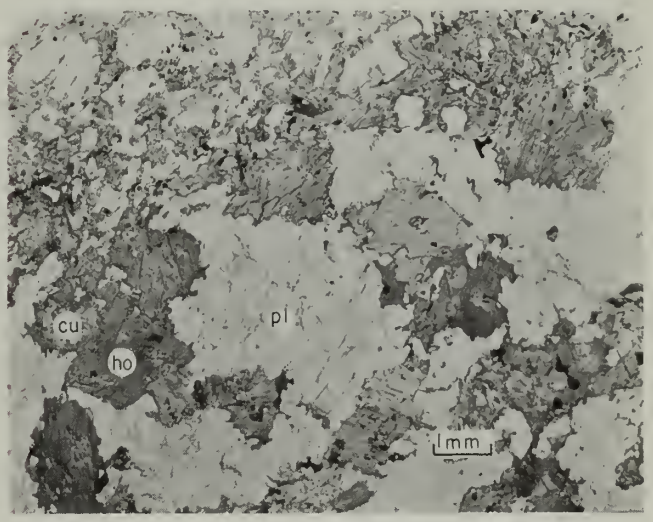
a ment, late-magmatic development of quartz K-feldspar, and remobilization of a low-melting t. The ambiguous textures of the Pine Flat r body have apparently been produced by in- n metamorphic recrystallization at high tempera- ll of these plutons, however, are sufficiently g neous on a large scale, and unambiguous in ld relations, that there can be little doubt of agmatic nature.

METAMORPHIC ROCKS

Distribution and Structure

e morphic rocks of Ben Lomond Mountain are s ely metasedimentary; approximately 90 percent u tzites and pelitic schists, and the remainder are l and calc-silicate rocks. These rocks form two r xposures and several smaller ones, with a total c about 9 square miles. The largest exposure n from Alba Road south to Bald Mountain and g Mill Creek; the other principal mass extends point 2.5 miles south of Felton to the north- e outskirts of Santa Cruz. A third, smaller u extends along San Lorenzo River from Para- P k to within half a mile of Santa Cruz. Isolated l lenses are at the head of Liddell Creek, west of ountain, and on San Vicente Creek 2.5 miles n st of Davenport (loc. 321); the latter locality n site of the Pacific Cement and Aggregates r

Marble is usually associated with schist and quartzite, and displays two distinct types of occurrence. More commonly, marble forms lensoid bodies that are generally less than half a mile long, although a few extend for a mile or more; many of these lenses are the sites of abandoned quarries. Marble lenses are sporadically distributed, but are especially abundant within a 2 mile radius of Santa Cruz. Marble within lenses is generally well bedded and commonly consists mostly of calcite with occasional thin schist interbeds. Contacts between marble lenses and adjoining schist and quartzite, locally well exposed on the former Henry Cowell estate northeast of Santa Cruz (present site of the University of California at Santa Cruz) [1] are abrupt and suggest faulting. In its other characteristic occurrence, marble forms massive beds alternating with schist and quartzite layers, as along Felton-Empire Grade near Bennett Creek, and on Ice Cream Grade near Laguna Creek.



Phata 6. Photomicragroph of hornblende-cummingtonite gobbro (SC 184–6–2) from Pine Flot bady, shawing contact between fine-groined (upper left) and caarse-grained phases. Nate segregatian of plagiaclose and omphiboles in caorse gobbro. cu = cummingtonite; ho = hornblende; pl = plogiaclose.

Schists are consistently foliated parallel to bedding planes. Associated quartzite displays a rod-like crinkling which plunges at low angles, subparallel to the strike of schistosity. Throughout the northern body of metasediments, bedding in schists and quartzites has a fairly consistent, east to northeast strike, with moderate dips ranging from north to south. These dips define several open folds. As pointed out earlier, the planar structure in orthogneiss near Laguna Creek, and lineations in the Smith Grade pluton, are generally parallel to schistosity of metasedimentary rocks, which suggests that these plutons may be synkinematic. Nonetheless, schist and quartzite adjacent to plutonic contacts, as along Laguna Creek, are commonly fractured and tilted, possibly by post-plutonic movements.

[1] At the time of field work in this area, ground had not yet been broken for the new U.C. campus.

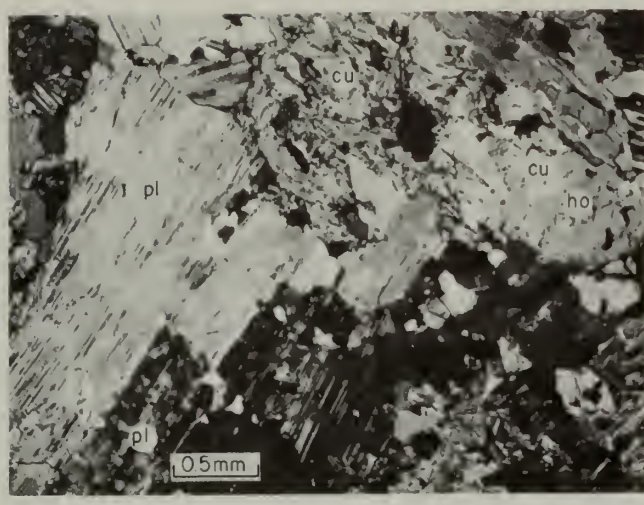


Photo 7. Photomicrograph of hornblende-cummingtonite gobbro showing pronounced "mottling" in plagioclase, caused by differential An content. Note the two distinct habits of cummingtonite: (1) smoothly intergrown with hornblende (right), and (2) in fibrous aggregates (top center). Nicols crossed. cu = cummingtonite; ho = hornblende; pl = plagioclase.

In the southern lens of metamorphic rocks, strikes are generally more variable, and no clear-cut structural pattern emerges. Exposed bedding planes in marble lenses near Santa Cruz display random attitudes, commonly diverging sharply between adjacent lenses or even within a single large lens, as at the head of Wilder Creek.

Discordant attitudes in marble, the common fault relationship between marble and schist, and the local fractured and dislocated aspect of quartzitic rocks, indicate considerable post-intrusion disturbance. Tertiary (mostly Miocene) sedimentary rocks on the southwestern and southern flanks of the mountain, on the other hand, display moderate and uniform southwest dips. This suggests that dislocations within the crystalline block were largely pre-Miocene, whereas major movements on the Ben Lomond fault and associated faults were post-Miocene.

Quartzite

More or less pure quartzites consist of a mosaic of quartz grains with sutured boundaries, usually with some disseminated red-brown biotite. Textures range from granoblastic to lepidoblastic. Some rocks resembling pure quartzite in hand specimen were found to contain 10 to 40 percent K-feldspar in small, clear, untwinned grains. Rocks consisting dominantly of quartz and calcite are commonly interbedded with marble. Contacts between quartzite and pelitic schist may be sharp, or more or less gradational.

Pelitic Schists

Pelitic schists range from simple quartz-biotite-muscovite rocks to more complex types that contain sillimanite, cordierite, and garnet. The principal mineral assemblages may be summarized as follows (quartz and biotite are present in each): K-feldspar-(plagioclase); muscovite-sillimanite-almandine-plagioclase; and sillimanite-cordierite-K-feldspar-(almandine).

Quartz-mica schists are widely distributed, commonly interlayered with quartzite, as al g ton-Empire Grade. Such rocks typically cor mosaic of quartz grains, with or without sul clear, untwinned K-feldspar, and sheaves of in muscovite and pale to deep red-brown bi highly micaceous rocks, crushing and gr along subparallel shear planes have produced sericitic aggregates which obliterate origir sheaves. Similar aggregates in unsheared rock readily explained, but could be related to thermal alteration.

Garnet porphyroblasts up to 1–2 cm in dian common, and typically show some retrogra ation to chlorite; in cordierite-bearing rocks, involved in more complex reactions (see Garnet from a sillimanite-bearing schist along Empire Grade (loc. 57A) has an estimated c tion, based on refractive index and unit cell 75 percent almandine, 11 percent spessartite, 2 pyrope and 2 percent grossularite.

Schists containing sillimanite and cordierite a paratively rare, and are confined to within a f dred feet of major intrusive contacts. Sillimani ing schist occurs on Felton-Empire Grade near Creek (loc. 57A); at the southeastern edge of Park (loc. 381); in a tongue of metasediments east of Paradise Park (loc. 383E); along Cave adjacent to Empire Grade (loc. 349–352B); Laguna Creek west of the Bonny Doon su (loc. 217A). Rocks at the latter three localit contain cordierite. The first four localities jacent to the Ben Lomond pluton, and the last gabbro body near Pine Flat Road. No similar rences were noted adjacent to the granodiorite gneiss or the Smith Grade pluton, although w nite is developed in marble near the latter in

Sillimanite forms stout prisms or wispy, fi tufts, both sometimes associated in the same shows evidence of originating in part from Cordierite-bearing rocks are marked by more c mineral assemblages than other pelitic rocks area, and also show incipient mineral reactions are characteristic of thermal metamorphism su posed on regional assemblages. A particularly tive rock in this connection, which forms a th crossing Laguna Creek about 100 yards south contact with the Pine Flat gabbro body (loc. contains K-feldspar, cordierite, sillimanite, garn gioclase (An_{27}), biotite, quartz and muscovite proximate order of decreasing abundance (ph The rock is well foliated, the planar element by aligned biotite, sillimanite, stretched garne elongate cordierite patches, with quartz and fe as a granoblastic mesostasis. Observed mineral tions include replacement of biotite by cordieri sillimanite; replacement of both muscovite and by K-feldspar; and limited replacement of gar cordierite, K-feldspar, and quartz, (cf. Chinner, A somewhat similar rock occurs northeast of P Park in a tongue of metasediments adjacent to diorite (loc. 383E). Contact hornfelses of calc composition are described elsewhere.

o Photomicrograph of sillimonite-cordierite-gornet schist (SC Juno Creek, 0.3 mile south of its crossing with Pine Flot N development of fibrous sillimonite from gornet ond biotite. sil anite; co = cordierite; go = gornet; bi = biotite.

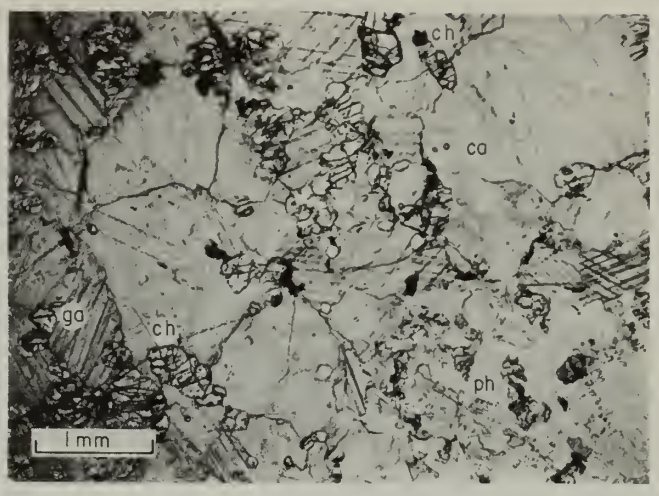


Photo 9. Photomicrograph of chondrodite-beoring morble (SC 251B); Reggiordo Creek, obout 0.1 mile north of Smith Grode crossing. ch = chondrodite; co = colcite; ph = phlogopite; go = gornet.

Marble and Calc-silicate Rocks

arely crystalline marble makes up an estimated r nt of the metamorphic rocks of the crystalline l. Calcareous rocks consisting chiefly of calc- eninerals, here referred to as calc-silicate rocks, e tively sparsely represented by local contact ees, occasional beds interlayered with schist or z , and sporadic xenoliths enclosed by gabbro.

re. The color of marble ranges from white, e coarse-grained and pure, to shades of gray, n pink or green, where finer-grained and/or con- a d. Most of the marble contains over 95 per- c cite; individual grains have a size range from h 0.1 mm to more than 3 cm, with an average 5 m. The most common accessory minerals are i and phlogopite, which are usually concen- l ong relic bedding planes. Other minerals that b n identified in marble include (in approximate f decreasing abundance): quartz, tremolite, i , forsterite, serpentine, sepiolite, sphene, wol- i , chondrodite, scapolite, garnet, hornblende, e spinel, pyrite, arsenopyrite, and sphalerite. Dis- i n of these minerals is not uniform, and only i five are common. Certain silicates such as l , wollastonite, garnet, and chondrodite occur r ely; and, with the exception of pyrite, the i true for the sulfides.

c e minerals are especially prominent in the e t Spring Street (Pacific Limestone Products q arry (loc. 270). Some boulders here consist of i sheaves of pale green tremolite-actinolite 10– n ong, and others contain forsterite, tremolite, c ite, chondrodite, and sepiolite. Silicate-bearing s arallel to the gently dipping bedding are vis- n he quarry wall.

o drodite also occurs in marble at Reggiardo c orth of Smith Grade (photo 9), and its pres- h e may be explained by influx of fluorine re- t emplacement of the Smith Grade pluton. This intrusion is also thought to account for the crystallization of wollastonite-calcite marble adjacent to Smith Grade in the same marble body (loc. 239). This is the only occurrence of wollastonite noted in the region; elsewhere, as in marble beds along Felton-Empire Grade, quartz and calcite are associated without any trace of wollastonite.

Scapolite occurs in impure marble at Cave Gulch near the crossing of Empire Grade, at Spring Street quarry, and south of Paradise Park. In each case scapolite is confined to relatively narrow bands and is associated with other silicates, including plagioclase, diopsidic pyroxene, hornblende, epidote, and grossular-rich garnet; its presence apparently depends primarily on the initial bulk composition of the rocks in which it occurs.

Calc-silicate Rocks. Dense, red-brown to greenish hornfels consisting of anorthite (An_{96}), iron-rich clinopyroxene ($Di_{28}He_{72}$), and garnet (65 percent grossularite, 25 percent andradite, and 10 percent almandine) crops out along Empire Grade adjacent to the gabbro body near Pine Flat Road (loc. 117). Sporadic boulders within the gabbro consist of anorthite, diopsidic pyroxene (approximately $Di_{85}He_{15}$), pale brown hornblende, and quartz, sometimes with calcite and clinozoisite, and are regarded as calcareous xenoliths. Calc-silicate hornfelses occur elsewhere adjacent to intrusive contacts (e.g., loc. 321, 421A).

Dense, unfoliated rocks containing anorthite and other lime-bearing silicates such as tremolite, diopside, epidote, and grossular-rich garnet, are interbedded with schist and quartzite in isolated localities. Their texture is distinctly granoblastic; schistosity is subdued or lacking, although compositional banding may be preserved. Such rocks apparently owe their texture to the lack of platy or prismatic minerals.

Belts up to 200 feet wide of finely banded, intricately folded calcareous rocks are associated with schist and marble along the lower reaches of Wilder Creek. The dominant types here are quartz-andesine-hornblende-calcite rock and micaceous quartzite. Pods and lenses of coarsely crystalline quartzite in marble

farther north along Wilder Creek are interpreted as recrystallized chert lenses.

Metamorphism in the Ben Lomond Mountain Area

Mineral parageneses as well as textural features of the metamorphic rocks suggest conditions of formation intermediate between "regional" and "contact" metamorphism. Regionally metamorphosed rocks refer in the present context to rocks formed under conditions of high temperature and moderate to high pressure with a distinct element of directed stress. Most of the metamorphic rocks of the Ben Lomond area fall in this category. Mineral assemblages of pelitic rocks, notably those containing sillimanite-almandine-K-feldspar, are indicative of the upper part of the almandine amphibolite facies.

Contact metamorphism, that is, essentially static thermal metamorphism, has been operative at least locally to produce hornfelses and coarser granoblastic rocks of the hornblende and pyroxene hornfels facies. Such rocks are especially evident near intrusive margins and represent a contact aureole, though a spotty and discontinuous one.

The relation between schistose and granoblastic rocks suggests that thermal metamorphism related to the intrusion of plutons has been superimposed on regionally metamorphosed rocks. Polymetamorphic conditions are illustrated especially in cordierite-bearing rocks such as those along Laguna Creek south of the Pine Flat gabbro body, in Cave Gulch, and near Paradise Park. Mineral reactions in these rocks, specifically development of cordierite and K-feldspar at the expense of biotite and garnet, have been well documented in contact aureoles (Chinner, 1962).

The presence of sillimanite as the only Al_2SiO_5 polymorph in the contact rocks, together with instability or absence of muscovite, also point to high temperature and moderate pressure during thermal metamorphism. Recent experimental evidence (Bel
Velde, 1964; Schreyer and Yoder, 1964; Faw
Yoder, 1966, p. 378, fig. 7) indicates that, w
stability field of sillimanite and of cordierite
down of muscovite (to K-feldspar and coru
could take place at about 680°C, at a minim
sure of about 2 kilobars (P_{H_2O}). In terms of m
phic facies, these conditions correspond to t
temperature end of the hornblende hornfels fa
its boundary with the pyroxene hornfels facie
ner and Verhoogen, 1960, p. 519–526).

The effect of contact metamorphism in ca
rocks is illustrated by development of wollast
siliceous marble adjacent to the Smith Grade
and garnet-Fe diopside hornfels adjacent to the
body near Pine Flat Road. Both of these ro
respond to the pyroxene hornfels facies. A
$P_{CO_2} = P_{total} = 2$ kilobars, the wollastonite r
gests a maximum temperature of formation
700°C (Ellis and Fyfe, 1956). Elsewhere in
(e.g., along Felton-Empire Grade), calcite an
coexist stably. Other silicate phases in marbl
from contacts (mainly tremolite, forsterite, an
side) may be correlated with the lower temp
(and possibly higher pressures) of the hor
hornfels or almandine amphibolite facies.

In the light of what has already been stated
ing structures and relative age relations am
various intrusive bodies, the most probable s
of events in the metamorphic history of the r
as follows. A sequence of shale, quartzite, lim
and marl underwent regional metamorphism,
panied by granitic intrusions (Smith Grade plu
granodiorite orthogneiss near Laguna Creek).
quent intrusions (Pine Flat gabbro body and B
mond pluton) then produced an overprint of
metamorphism on metasedimentary rocks adja
their borders. Nothing is presently known con
the interval between the two intrusive period

[1] Corundum was not observed in the rocks under discussion, a
not be expected in the presence of free quartz.

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HITTENDEN, CALIFORNIA, EARTHQUAKE OF PTEMBER 14, 1963*

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ABSTRACT

erthquake of magnitude 5.2 on the Richter scale re at 19:46 GCT September 14, 1963, in the Mon- B/ region of west-central California. The damage ucres and the eyewitness accounts indicate that the nu intensity of VII on the modified Mercalli scale re at Chittenden, Santa Cruz County, California, h the earthquake was associated with movement te San Andreas fault. Apparent errors in locating pienter by computer methods were as large as 30 et s. Geologic effects from the earthquake included ics along oversteepened road and quarry cuts and rase in spring flow. No evidence of surface rupture te San Andreas fault was found.

INTRODUCTION

eigation of the Chittenden earthquake by the Geological Survey was undertaken at the request icwas funded by, the U. S. Advanced Research c Agency as part of its Vela Uniform Program. p pose of the investigation was to determine the tnd character of the surface effects of the earth- e.The work was performed in collaboration with Throop and R. M. Biniki of Itek Corporation, Hped gather information for the intensity map ovided aerial photography, a mosaic of the Chit- rarea, and other materials. W. R. Walker of Itek otion served as coordinator and made available ent, personnel, and work space. W. H. West- c Stanford Research Institute and Don Tocher Michael Blackford of the University of California cinterpret the intensity data and provided in- aon from seismic records concerning the loca- o the epicenter.

LOCATION OF THE EARTHQUAKE

e earthquake occurred at 19:46 GCT (12:46 PDT) on September 14, 1963. Preliminary n analyses of seismic records by Michael Black- d the Seismological Station, University of Cali- aon September 17, placed the epicenter in the tey Bay region of west-central California, near chool (fig. 1), lat 36°50′ N., long 121°40′ W. The magnitude of the event, according to Blackford, was 5.2 on the Richter scale; the focus was estimated to have been between 7 and 10 kilometers deep.

Field studies on September 19 indicated that there was no earthquake damage in the vicinity of Lake School and that the maximum damage appeared to be in the vicinity of Chittenden. In order to determine if the type and amount of damage were related to a particular fault, the writer decided to prepare an intensity (damage) map of the San Juan Bautista quadrangle. Earthquake interview forms (see Appendix A), obtained from W. H. Westphal of Stanford Research Institute, were used in gathering information from residents in the quadrangle. R. M. Biniki and J. E. Throop of Itek Corporation were briefed on the use of the forms and the modified Mercalli scale of Wood and Neumann (1931, see Appendix B). Mr. Biniki interviewed persons mainly in the area between Hecker Pass and Watsonville; Mr. Throop interviewed persons mainly in the Prunedale-Lake School area; and the writer interviewed persons and checked for damage in the remainder of the quadrangle.

The data from the intensity investigation were analyzed by the writer and used to prepare the intensity isoseismals shown on figure 1. The maximum intensity of approximately VII on the modified Mercalli scale of Wood and Neumann (1931, see Appendix B) occurred along and parallel to the San Andreas fault, indicating that the earthquake was associated with movement along this feature. The epicenter is shown for convenience at Pajaro Gap in the center of the area of maximum intensity.

On October 2, 1963, Don Tocher of the Seismological Station, University of California, gave the writer a revised location for the epicenter based on a computer analysis of seismic records from 16 stations. His revised location (fig. 1) is lat 36°52′18″ N., long 121°38′48″ W., about 4.9 kilometers southwest of the epicenter determined from intensity data.

In November, the U. S. Coast and Geodetic Survey (1963) gave as a preliminary location for the epicenter (based on travel-time records of 27 stations) lat 36°52′ N., long 121°48′ W. This location is near Fort Ord and 30 kilometers southwest of the epicenter determined from intensity data. An error of this magnitude, according to W. H. Westphal, could be due to clock errors and/or difficulties in distinguishing the first arrival of the earthquake (P) waves from seismic "noise".

Wells and others (1961) and Westphal and Lange (1962) have determined that some inaccuracies in the

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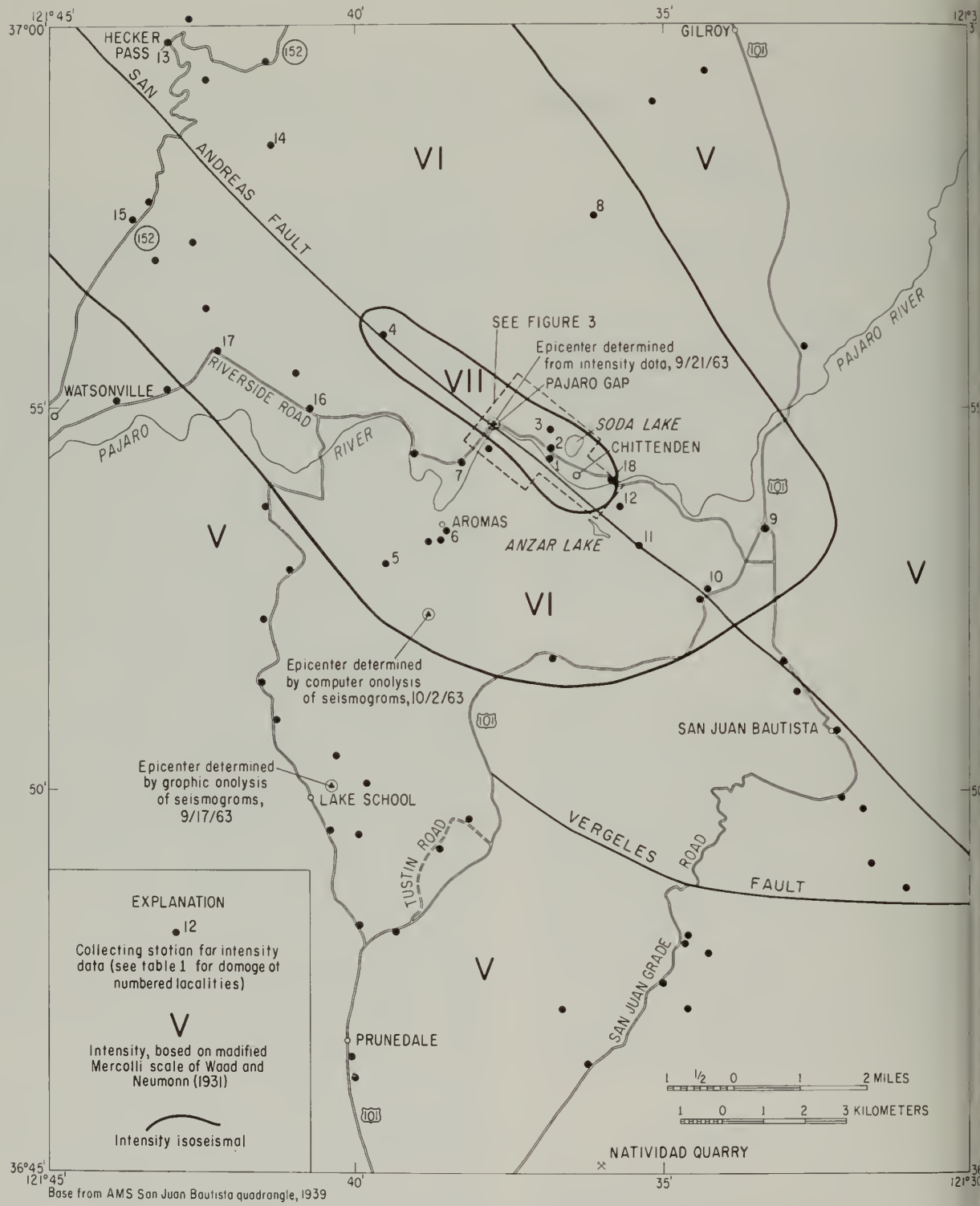


FIGURE 1. Locality and intensity map of the Chittenden earthquake of September 14, 1963.

o of epicenters in the Chittenden-Hollister area
ls be due to refraction of seismic waves along
r ults. To minimize this error and to provide
at seismic-velocity data in the region, Hamilton
oters (1964) measured the seismic energy of
riginating in the Natividad quarry (fig. 1)
Chittenden. According to Don Tocher, if
smic calibration data had been used in the
erty of California computer solution for the
nr of the September 14, 1963 earthquake, then
penter would have plotted closer to the one
mied from intensity data.

te the manuscript and illustrations for this re-
ha been submitted for publication, Udias (1965)
shd an analysis of seismic information pertaining
e eptember 14, 1963 earthquake. He evidently
t: local seismic calibration data of Hamilton
ot:rs (1964) and determined that the epicenter
it at 36°52′ N., long 121°38′18″ W., about 5
ie rs south of the epicenter determined from in-
y lata, and 1.3 kilometers east-southeast of the
nr determined by Tocher on October 2, 1963.
; ives 2 kilometers as the minimum error in
n the epicenter. He also gives a depth of 3.3
ie rs for the focus of the earthquake, but he
ics that this figure is less accurate than the one
h location of the epicenter. He evidently used
e ords of five permanent seismograph stations
n irtually surround the Chittenden area within
ace of 70 miles, plus those from three mobile
n in the Chittenden area, to determine the epi-
r nd focus.

s nmary, the epicenters of the September 14,
e thquake determined by different methods of
z g seismograms do not agree with the epicenter
mied from field data by as much as 30 kilo-
rsind by as little as 5 kilometers, plus or minus
i um of 2 kilometers. This disagreement is in a
n with a relatively dense spacing of seismographs
v ere local seismic calibration data are available.

DAMAGE

uctural damage caused by shaking during the
qake was most severe in the Chittenden area
fi 1 and Table 1). Some of the damaged struc-
:e shown on figure 2. The most severely dam-
s ucture (fig. 2A), an old two-story wood-frame
e had the second floor displaced and moved
westward about 2 inches towards the San An-
ult and away from a concrete retaining wall
t: wooden bearing wall of the house. The
d bearing wall also moved slightly away from
e ining wall.

ie was apparently some relation between the
s: of damage and whether a structure was on
o: or alluvium. Most of the damaged structures
r alluvium. Moreover, intensity reports received
h U. S. Coast and Geodetic Survey (written
mication from W. K. Cloud, March 22, 1965)
es amplification of intensity to VI in the towns
Vesonville, Capitola, Salinas and San Jose, all
r in by relatively thick deposits of alluvium,
p ed to an intensity of V or less from Prunedale to San Juan Bautista (see fig. 1) and in other areas near or on bedrock. Kennitzer (1921), who investigated an earthquake of similar magnitude in the Chittenden area on July 24, 1921, noted a similar relationship and stated that the intensity of the earthquake shock was, without exception, somewhat higher in Watsonville, Salinas and other towns built upon alluvium than at places at equal distances from the epicenter that were on solid rock.

Table 1. Summary of damage caused by the Chittenden earthquake.

Latitude	Longitude	No. on fig. 1	Damage
36°54′23″N	121°36′49″W	1	Second floor of wood frame house moved about 2 inches southwestward; doors, pipes and plaster cracked; stove, hot water heater, dresser and other furniture moved, and lamps overturned.
36′54′20″N	121°36′49″W	1	Stone chimney cracked and one stone shaken loose; legs and ladder of feed silo bent and twisted.
36°54′28″N	121°36′49″W	2	Upper part of wood frame house moved relative to foundation, causing ceiling to separate slightly from wall; water tank slammed into wall; dishes, vases and lamps overturned and broken.
36°54′29″N	121°36′51″W	2	Brick chimney cracked and one brick shaken loose.
36′54′40″N	121°36′42″W	3	Water tank shifted on foundation; pipes broken.
36°55′09″N	121°38′14″W	4	Water pipes broken.
36°52′56″N	121°39′32″W	5	Jam jars shaken off shelf.
36°53′20″N	121°38′30″W	6	Many cans shaken off shelves in grocery store.
36°54′15″N	121°38′13″W	7	Many bottles shaken off shelf in bar.
36°57′30″N	121°36′08″W	8	Pictures and vases shaken off shelves.
36°53′26″N	121°33′19″W	9	Few cans shaken off shelf.
36°52′29″N	121°34′22″W	10	Vases shaken off shelf and jars shaken out of refrigerator.
36°53′10″N	121°35′19″W	11	One can shaken off shelf.
36°53′42″N	121°35′43″W	12	Plates and vases shaken off shelf.
36°59′41″N	121°43′02″W	13	Dishes shaken off shelf; house settled.
36°59′17″N	121°42′36″W	14	Dishes shaken off shelf.
36°57′23″N	121°43′35″W	15	Cans and bottles shaken off shelves.
36°54′50″N	121°40′00″W	16	Objects shaken off shelf.
36°55′42″N	121°42′17″W	17	Objects shaken off shelf.
36°54′00″N	121°35′48″W	18	Bridge footing slightly damaged.

GEOLOGIC EFFECTS

Field studies of the geologic effects of the earthquake were facilitated by a check list compiled by M. G. Bonilla and E. H. Bailey (1963, 1964). The principal surficial features listed as possibly produced during an earthquake include faults, scarps, fissures, distorted linear or planar elements, landslides, subsidences, and discharges of water and unconsolidated materials.

A

B

C

D

FIGURE 2 - Damaged structures at Chittenden. A, The second floor of this house moved about 2 inches away from the concrete retaining wall (arrow). B, The legs and ladder of this feed silo were twisted and bent during the earthquake. C, This chimney was cracked and had a brick (arrow) shaken loose in spite of a metal earthquake-resistant lining. D, The footings of this highway bridge across the Pajaro River were slightly damaged by shaking during the earthquake.

races of the San Andreas and Vergeles faults were examined at several localities to determine whether any slippage had occurred during the quake. No surface rupture was found. No evidence of surface movement along these faults during the earthquake was seen on infrared, panchromatic, or color photographs (Itek Corporation photos September 21, 1963).

Fissures (figs. 3 and 4) developed in Riverside Road in Chittenden Pass. The fissures are parallel to the San Andreas fault and the steep slope that forms the wall of the pass. The downslope side of the fissure dropped downward as much half an inch and outward as much as 1 inch. Inasmuch as the road at this locality is cut across an active landslide, the fissures probably developed partly by lurching and partly by settling of the unconsolidated landslide material.

Four small landslides developed along oversteepened road and quarry cuts in the vicinity of Chittenden during the earthquake. Slides along a road 600 feet northwest of Soda Lake (figs. 3 and 5) involved unconsolidated dry soil and extensively weathered Monterey shale. Part of a large landslide, consisting of disturbed mixture of soil and shale at Pajaro Gap, moved again and rerouted the drainage to form a small pond (figs. 3 and 6). Loosely consolidated crushed shale along steep cuts at Logan quarry and a small quarry 2,500 feet northwest of Soda Lake slid during the earthquake and covered part of the quarry floor. The slides raised dust which attracted the attention of residents in the Chittenden area during the earthquake.

The shorelines of Anzar and Soda Lakes and the banks of the Pajaro River near Chittenden were searched carefully for mud volcanoes and other features related to the discharge of water and unconsolidated materials. Soda and Anzar Lakes, in particular, were watered mudflats at the time of the earthquake and might have developed mud volcanoes if shaken sufficiently.

Park rangers at Madonna County Park near Hecker Pass reported an increase in the flow of a spring within the park commencing two days after the earthquake and lasting two or three days. No other anomalous spring or stream flow was reported, but the hydrologic aspects of the earthquake were not thoroughly and systematically investigated.

In summary, geologic effects from the September earthquake were confined to slides in poorly consolidated material along oversteepened road and quarry cuts and to an increase in the flow of springs. No surface fissures, distorted linear or planar elements, sand craters, or subsidences attributable to the earthquake were reported on natural slopes. These observations are similar to those of Westphal and Lange (1962, p. 10), who investigated an earthquake of similar magnitude near Hollister, 12 miles southeast of Chittenden.

PREVIOUS FAULT AND SEISMIC ACTIVITY

Active faults with "recent" movement have been mapped in the San Juan Bautista quadrangle by Allen and Kerr and Schenck (1925), but only the San Andreas and subsidiary faults less than 1 mile from the principal trace have caused unquestionable surface ruptures during the past 75 years. During the 1906 earthquake, movement along the San Andreas fault caused horizontal displacement of 4 feet, 3 miles southeast of Chittenden, and of at least 3½ feet at the west end of the railroad bridge about 1 mile northwest of Chittenden (California Earthquake Investigation Comm., 1908, p. 38, 278–279). Displacement of the railroad bridge, fissuring along the San Andreas fault, and landsliding also occurred during the earthquake of April 24, 1890 (Townley and Allen, 1939, p. 81).

With respect to seismic activity, the San Juan Bautista quadrangle is one of the most active areas in the conterminous United States. Wood and Heck (1961, fig. 2), Townley and Allen (1939) and the U. S. Coast and Geodetic Survey (1952–1962) have plotted or described 21 major earthquakes of intensity V–VI or stronger that occurred within a radius of 30 kilometers from Chittenden during the past 160 years on the following dates:

October 11(?), 1800; March 6, 1882; March 30, 1883; March 30, 1885; April 24, 1890; June 20, 1897; April 30, 1899; July 6, 1899; April 18, 1906; March 10, 1910; July 24, 1921; June 22, 1947; December 31, 1948; December 16, 1953; April 22, 1954; April 25, 1954; August 12, 1954; March 2, 1959; May 26, 1959; December 28, 1959; January 19, 1960.

Seismic events of intensity less than V in the same area could number in the thousands annually; for example, an investigation by Westphal and Lange (1962) recorded 281 seismic events in a 98-hour period following an earthquake near Hollister, 40 kilometers southeast of Chittenden. Udias (1965) studied seismic records for the years 1960 through 1963 and determined that there is a continuous activity of about 2 or 3 earthquakes of magnitude 2.5 to 3.5 per month.

CONCLUSIONS

The Chittenden area is an excellent scientific laboratory to study the causes and effects of earthquakes. The area is one of the most active, seismically, in the United States. It is virtually surrounded by modern and precise seismographs. Local seismic calibration data are available. The area is moderately populated, a favorable factor in the preparation of intensity maps. Reasonably good geologic maps are available.

In spite of these favorable factors, the difference between field and laboratory methods of locating the September 14, 1963 epicenter was as great as 30 kilometers. There were no direct measurements of ground acceleration, and little attention was paid to effects that could have contributed additional information, such as the effects on water wells and on large bodies of water. There was little coordinated effort to study the earthquake and the results of separate investigations were not discovered by the writer until they were published. Obviously there is a need for a more coordinated and more complete study of earthquakes in the Chittenden area before discrepancies in the field and laboratory studies can be resolved.

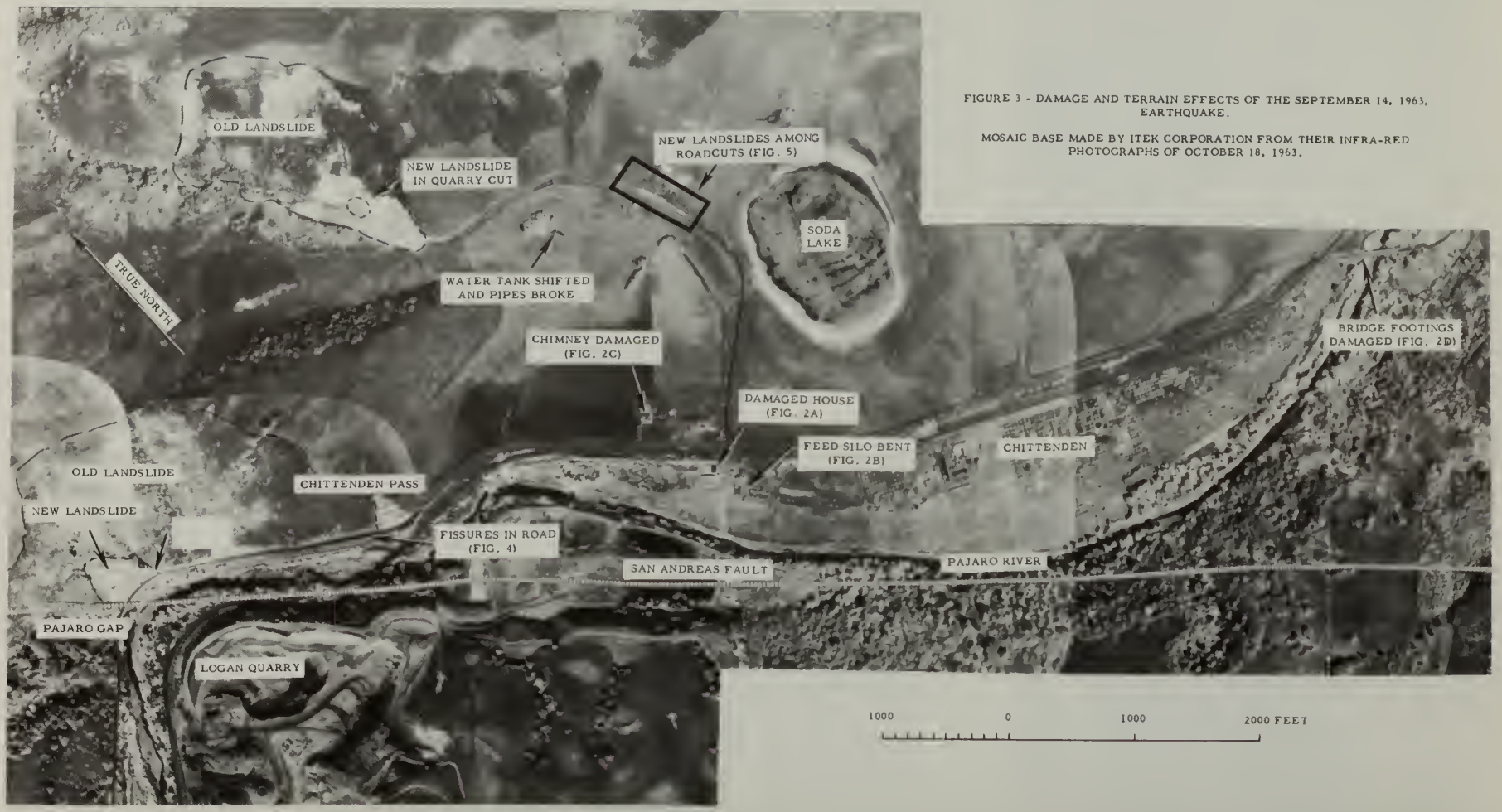
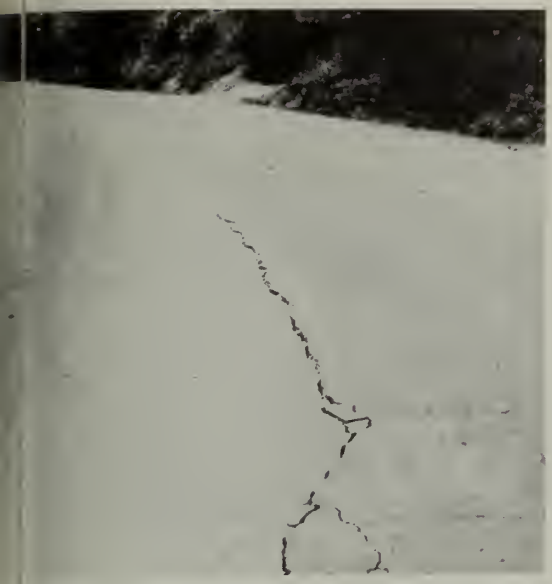


FIGURE 3 - DAMAGE AND TERRAIN EFFECTS OF THE SEPTEMBER 14, 1963, EARTHQUAKE.

MOSAIC BASE MADE BY ITEK CORPORATION FROM THEIR INFRA-RED PHOTOGRAPHS OF OCTOBER 18, 1963.



A

B

FIGURE 4 - Fissures in Riverside Road at Chittenden Pass. A, Crack extending northwest towards Pajaro Gap. B, Detail of crack showing maximum width of break.

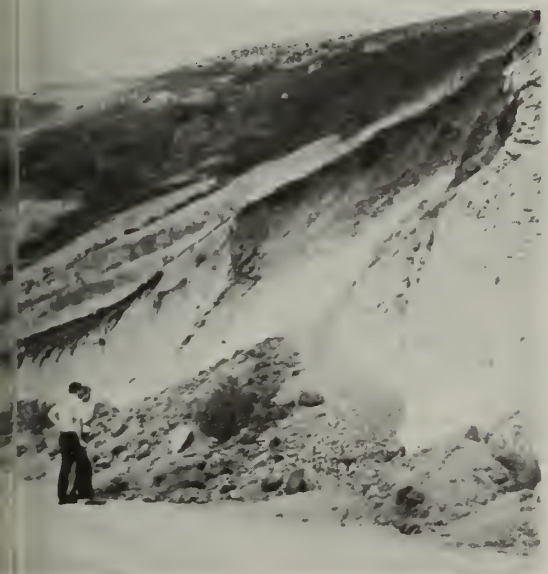


FIGURE 5 - Landslide along over-steepened roadcut northwest of Soda Lake.

FIGURE 6 - Spring at base of new landslide near Pajaro Gap.

APPENDIX A

Date_____
Time_____ PST/PDT
Magnitude_____
Intensity_____

EARTHQUAKE INTERVIEW REPORT

Place: Sec. _____T._____R._____Interviewed by_____

Information Source: _____

1. Motion: Rapid, slow,_____Shook how long_____
2. Felt by: Several, many, all; by observer_____
3. Location: Home, in community, or_____
4. In building: Wood, brick, masonry A,B,C,D,_____ strongly, weakly built; on_____1, 2,_____floor, lying down, sitting, active,_____
5. Outdoors: By observer, by others; quiet, active,_____
6. Direction of motion felt: Outdoors, indoors,_____
7. Ground underneath locality: Rock, soil, loose, compact, marshy, filled in,_____, level, sloping, steep
8. Awakened: No one, few, many, all; in home, in community
9. Frightened: No one, few, many, all; in home, in community
10. Rattled: Windows, doors, dishes,_____
11. Creaked: Walls, frame,_____
12. Hanging objects: Doors, lamp,_____did, did not, swing N, NE, E, SE, S, SW, W, NW
13. Shook trees, bushes: Slightly, moderately, strongly,_____
14. Shifted small objects: Vases, dishes,_____
15. Overturned: Vases, etc., small objects, furniture,_____
16. Cracked: Plaster, windows, walls, chimneys, ground,_____
17. Caused to fall: Knickknacks, books, pictures, plaster, walls, chimney,_____
18. Broke: Dishes, window, furniture,_____
19. Caused damage: None, slight, considerable, great, total in wood, brick, masonry, concrete,_____

Remarks:

APPENDIX B

MODIFIED MERCALLI INTENSITY (DAMAGE) A OF 1931 (Abridged)

I. Not felt except by a very few under especially favo le cumstances. (I Rossi-Forel Scale.)

II. Felt only by a few persons at rest, especially on up of buildings. Delicately suspended objects may ng to II Rossi-Forel Scale.)

III. Felt quite noticeably indoors, especially on upper buildings, but many people do not recognize it as ea quake. Standing motorcars may rock slightly. Vra like passing truck. Duration estimated. (III Ro-F Scale.)

IV. During the day felt indoors by many, outdoors by w night some awakened. Dishes, windows, doors d walls make creaking sound. Sensation like hea striking building. Standing motorcars rocked no (IV to V Rossi-Forel Scale.)

V. Felt by nearly everyone; many awakened. Some windows, etc., broken; a few instances of cracked unstable objects overturned. Disturbances of tre and other tall objects sometimes noticed. Pendulu may stop. (V to VI Rossi-Forel Scale.)

VI. Felt by all; many frightened and run outdoors. Son furniture moved; a few instances of fallen plaster da aged chimneys. Damage slight. (VI to VII Ro F Scale.)

VII. Everybody runs outdoors. Damage negligible in bui good design and construction; slight to moderate built ordinary structures; considerable in poorly ilt badly designed structures; some chimneys broken. by persons driving motorcars. (VIII Rossi-Forel Sle.

VIII. Damage slight in specially designed structures; con in ordinary substantial buildings, with partial lap great in poorly built structures. Panel walls throw out frame structures. Fall of chimneys, factory stacks, monuments, walls. Heavy furniture overturned. Sl a mud ejected in small amounts. Changes in wel at Persons driving motorcars disturbed. (VIII+ to I Ro Forel Scale.)

IX. Damage considerable in specially designed structur we designed frame structures thrown out of plumb; at substantial buildings, with partial collapse. B di shifted off foundations. Ground cracked conspi us Underground pipes broken. (IX+ Rossi-Forel Sc.)

X. Some well-built wooden structures destroyed; most so and frame structures destroyed with foundations. ou badly cracked. Rails bent. Landslides considera fr river banks and steep slopes. Shifted sand and mud Va splashed (slopped) over banks. (X Rossi-Forel Sca

XI. Few, if any (masonry), structures remain standing. idg destroyed. Broad fissures in ground. Undergrou pipe lines completely out of service. Earth slumps a la slips in soft ground. Rails bent greatly.

XII. Damage total. Waves seen on ground surfaces. Lines sig and level distorted. Objects thrown upward into t air.

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...ES ON THE TYPES OF CALIFORNIA SPECIES OF ...E FORAMINIFERAL GENUS ORTHOKARSTENIA ...TRICH, 1935

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ABSTRACT

...clusions drawn from an examination of the type ...atenid foraminifers and other specimens referable ...ongate calcareous genus from Late Cretaceous ...o California are: 1) *Siphogenerinoides clarki* var. ...Cushman and Goudkoff, 1944, is a subjective ...of *Orthokarstenia whitei* (Church, 1943) [*Siphoides* and *Siphogenerita* of authors]; and 2) most ...atenids from the type locality of *Orthokarstenia* ...i Fresno County either may be conspecific with *...atenia cretacea* (Cushman) from the Colon Shale ...ela, or may constitute a new species of *Orthokarstrich*, 1935.

...arstenia whitei (Church)—in addition to *O. clarki* ...c and Campbell)—(the only other representative ...nus * described from California) and the unas...thokarstenid mentioned above—seem to be lim...he Maastrichtian Stage in California; however, ...ers identified by some authors as *O. whitei* (or ... var. costifera) and *O. clarki* (under the generic *Shogenerinoides*) may have a Campanian-Maas...range in South America or a Conician-Campanian ...West Africa.

...discussions about significant zonal or stage ...fers of Late Cretaceous age in California re... confusion exists among micropaleontologists ...distinguishing features of several representa...the elongate calcareous genus *Orthokarstenia* ... 1935, previously recorded as taxa of *Sipho...ides* Cushman, 1927. The description and/or ...ns of some of these fossils—particularly those ...ntra Costa and Fresno Counties—first referred ...*generinoides clarki* Cushman and Campbell ...*S. whitei* Church (1943), and *S. clarki* var. ... Cushman and Goudkoff (1944), later trans... the genus *Siphogenerita* by Furrer (1961), ...ified now as orthokarstenids, in part at least, ...lich and Tappan (1964), Tappan (1964), and ... re seemingly inadequate and subject to vari...pretations.

We have been perplexed mainly by the so-called diagnostic characteristics of "*Siphogenerinoides*" *whitei* and "*S.*" *clarki* var. *costifera*, and until recently differed as to their determinations as well as their stratigraphic allocation. To resolve our doubts, we found it necessary to restudy and to reillustrate the type specimens of these ancient protozoans. And, although there seems to be little doubt about the recognition of "*Siphogenerinoides*" *clarki*, a few observations about this foraminifer also may be meaningful because it, too, appears to be restricted to the youngest Cretaceous (Maastrichtian) rocks in California. Furthermore, "*S.*" *clarki* is one bit of evidence that faunal provinces like those in the Great Valley of California apparently existed as far south as Peru in the Western Hemisphere during the Late Cretaceous time.

Orthokarstenia clarki (Cushman and Campbell)

Figures 1–8

Siphogenerinoides clarki Cushman and Campbell, 1936, Contr. Cushman Lab. Foram. Research, vol. 12, pt. 4, pp. 91–92, pl. 13, figs. 9–12 (uppermost Cretaceous, black shale, Byron quadrangle, 15-minute edition, 1916; not Mt. Diablo quadrangle, 15-minute edition, 1898, Contra Costa County, California).

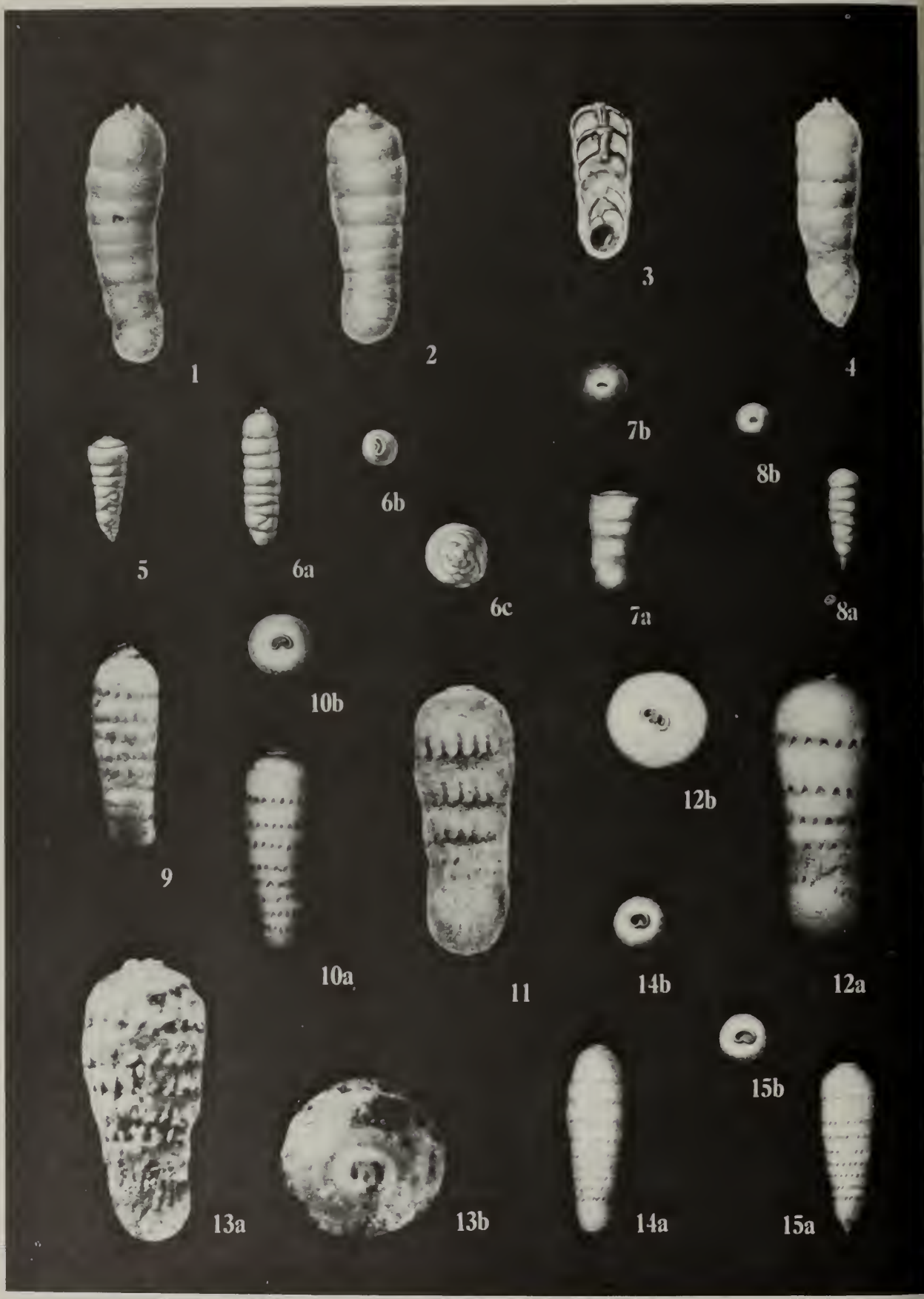
[?] *Siphogenerinoides clarki* Cushman and Campbell. Frizzell, 1943, Jour. Paleontology, vol. 17, no. 4, p. 349, pl. 56, fig. 30 (I. P. Co. well 2616, 1790 feet depth, Upper Cretaceous, "*Clavulina* shale", Department of Piura, northwestern Peru).

Siphogenerinoides clarki Cushman and Campbell. Stone, 1946, Jour. Paleontology, vol. 20, no. 5, p. 472.

[?] *Siphogenerinoides clarki* Cushman and Campbell. Bürgl and Tobon, 1954, Boletín Geológico, vol. II, no. 1, p. 37 (list) and plates 1–5. (Upper Cretaceous, Campanian-Maastrichtian, Colombia).

[?] *Siphogenerinoides clarki* Cushman and Campbell. Petters, 1955, Jour. Paleontology, vol. 29, no. 2, p. 219–list. (Upper Cretaceous, Campanian-Maastrichtian, Colombia).

...given at the S.E.P.M. meeting in Bakersfield, California, on ...965, Keith D. Berry of the Standard Oil Company at Oildale ...t he has found specimens of *Siphogenerita? (Orthokarstenia)* in ... Cenomanian strata in the Sacramento Valley of California.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Figures 1–8 (appasite). *Orthakarstenia clarki* (Cushman and Campbell).

1–4. *Siphagenerinaides clarki* Cushman and Campbell, 1936. x30. Halotype (fig. 1-megalospheric form); paratypes (figs. 2, 3-megolospheric farms; 4-micraspheric form). Uppermast Cretaceaus, black shale, Byron quadrangle, Contro Costa Caunty, Califarnia.

5–6. *Siphagenerita clarki* (Cushman and Campbell) of Furrer, 1961 (after Loeblich and Toppan, 1964). Topotypes (fig. 5-micraspheric test, x21; figs. 6o, b-megolaspheric test, x21; fig. 6c-microspheric test, x41). Upper Cretaceaus, Campanian, Byron quadrongle, Contra Costo County, Californio.

7–8. *Siphogenerinaides clarki* Cushman and Campbell af Martin, 1964. x30. Hypatypes (Figs. 7o, b-macraspheric test; figs. 8a, b-micraspheric test). Upper Cretaceaus (Maastrichtian), Uhalde Farmatian, Panoche Hills, Fresno County, Califarnia.

Figures 9–15. *Orthokarstenia whitei* (Church).

9. *Siphogenerinoides whitei* Church, 1941. x (nat given). Halotype. Upper Cretoceous, Moreno shale, [Morca shale], Panoche Hills, Fresno County, Colifarnia.

10. *Siphogenerinoides whitei* Church, 1941. x (nat known). Re-illustrated halotype.

11. *Siphogenerinoides clarki* Cushman and Compbell var. *costifera* Cushman ond Goudkoff, 1944. x50. Holatype. Upper Cretoceaus, "Chico Series," Jergins Oil Cheney Ranch No. 1 Well (depth af 6988 feet), Fresno County, California.

12. *Siphogenerinaides clarki* Cushman and Campbell var. castifero. Cushman and Goudkoff, 1944. x 50. Re-illustrated holotype.

13. *Siphogenerinoides whitei* Church af Cushmon and Gaudkaff, 1944. Hypotype (fig. 13a, x35; fig. 13b, x43). Upper Cretaceaus, "Chico Series," Jergins Oil Cheney Ranch Na. 1 Well (depth af 6274 feet), Fresna County, Califarnia.

14–15. *Siphogenerinoides whitei* Church af Martin, 1964, x16. Topotypes (figs. 14a, b-mocrospheric test; figs. 15a, b-microspheric test). Upper Cretaceous (Maastrichtian), Morca Shole Member of Marena Formation, Panache Hills, Fresna Caunty, Califarnia.

hgenerita clarki (Cushman and Campbell). Fur-
91, Proc. Biol. Soc. Washington, vol. 74, pp.
2, figs. 10, 11a–c. (Upper Cretaceous, Byron
agle, Contra Costa County, California).

hgenerinoides clarki Cushman and Campbell.
n 1964, Jahrb. Geol. Bundes., Sonderband 9,
. 93, pl. 12, figs. 5–6 a–b (Upper Cretaceous,
Uhalde Formation, Maastrichtian, Fresno
California).

thkarstenia clarki (Cushman and Campbell).
li and Tappan, 1964, Treatise Invert. Paleo.,
rotista 2, p. C567, fig. 446–11, 12a–c (Upper
cous, Campanian, California).

Description (in part): "Test elongate, slightly
r, circular in transverse section, greatest breadth
te apertural end, early stages triserial in the
sheric form, biserial or uniserial in the megalo-
iuniserial in the adult; chambers fairly distinct,
ey slightly inflated, somewhat overlapping, in-
r gradually in height as added; sutures fairly
d very slightly if at all depressed; wall fairly
conspicuously perforate, smooth, with faint
f longitudinal striations; aperture terminal, with
t lip, with one side convex, the other concave,
ially ending in two inwardly projecting tooth-
minences. Length 1.20–1.30 mm.; diameter
0 mm."

itory of Type Specimens: Holotype in the
n Collection (No. 23554), incorporated with
S. National Museum Collection, Washington
. Cushman and Campbell did not mention the
of the paratypes; however, Miss Ruth Todd
U. S. National Museum informs us that these
Cushman Collection Slide No. 23555, and that
e four specimens, instead of three as recorded
ly.

Stratigraphic Occurrence in California: Zone C′, an ecological equivalent of zone C (lower Ciervian Stage), and zone D-1 (upper Ingramian Stage), Upper Cretaceous, according to Goudkoff (1945, Tables I and II). Zones C, C′ and D-1 are correlative with the Maastrichtian Stage of the European Standard of the Cretaceous System (see Bandy, 1951; Popenoe, Imlay, and Murphy, 1960; Graham and Clark, 1961; Payne, 1962; Colburn, 1964; and Martin, 1964; among others). However, Loeblich and Tappan (1964) restrict *O. clarki* (Cushman and Campbell) to the Campanian—a stage designation not yet verified according to other biostratigraphers. (In Colombia and Peru, the only areas of appearance outside California with which we are acquainted, the stratigraphic range may be Campanian— Maastrichtian; see Petters, 1955, pp. 219–222; Bürgl and Tobon, 1954, pp. 37, 39, and 40).

The type locality of *O. clarki* (Cushman and Campbell), near the old Marsh house in the western part of the Byron quadrangle, is inaccessible at present due to inundation by pond waters.

Comments: Orthokarstenia clarki has chambers with straight and horizontal, or nearly so, lower margins in contrast to the scalloped or re-entrant type possessed by most members of this uvigerinid genus. As such, it resembles another foraminifer from Late Cretaceous strata—*Siphogenerinoides cretacea* Cushman subsp. *idkyensis* Colom (1948, p. 655, pl. 48, figs. 1–16) from the Campanian-Maastrichtian of the Spanish Sierra, likewise properly referred to as an orthokarstenid since its early chambers are triserially arranged.

Detailed studies of the internal siphon or columnar process, aperture, and general morphology of topotype specimens of *Siphogenerinoides clarki* by Furrer in 1961, along with his analyses of similar structures in *S. clarki* var. *costifera* and *S. whitei*, have added much to our knowledge of these Late Cretaceous foraminifers. Earlier, Stone (1946, pp. 463, 472, 473) also presented pertinent information about the same group of fossils.

Siphogenerinoides clarki Cushman and Campbell was selected by Furrer as the type of the genus *Siphogenerita,* a name he proposed (1961) for specimens similar to siphogenerinoidids but with triserial microscopic generation (also see Dupeuble, Verdier, and Vernhet, 1963, p. 211). Most micropaleontologists are, however, now of the opinion that *Siphogenerita* should be treated as a synonym of *Orthokarstenia* Dietrich, 1935.

Orthokarstenia whitei (Church)
Figures 9–15

Siphogenerinoides whitei Church, 1943, California Div. Mines Bull. 118, pt. 2, p. 182 (and errata following p. 773), fig. 67(37). (Upper Cretaceous, approximately 1100 feet below Moreno-Lodo contact in the basal portion of the Marca Shale member of the Moreno Formation, Panoche Quadrangle, Fresno County, California).

Siphogenerinoides whitei Church. Cushman and Goudkoff, 1944, Contr. Cushman Lab. Foram. Research, vol. 20, pt. 3, p. 58, pl. 9, figs. 17–18 (Upper Cretaceous, Jergins Oil Cheney Ranch No. 1 Well (depth of 6274 ft.), Fresno County, California).

Siphogenerinoides clarki Cushman and Campbell var. *costifera* Cushman and Goudkoff, 1944, Contr. Cushman Lab. Foram. Research, vol. 20, pt. 3, p. 58, pl. 9, fig. 19 (Upper Cretaceous, Jergins Oil Cheney Ranch No. 1 Well (depth of 6988 ft.), Fresno County, California).

[*non*] *Siphogenerinoides whitei* Church. Stone, 1946, Jour. Paleontology, vol. 20, no. 5, p. 473, pl. 72, figs. 8–12 (Upper Cretaceous, "*Clavulina* shale", Department of Piura, northwestern Peru).

Siphogenerinoides whitei Church. Martin, 1964, Jahrb. Geol. Bundes., Sonderband 9, Wien, pp. 93–94, pl. 12, figs. 7–9a-b (Upper Cretaceous—Range: Dosadas, Tierra Loma and Marca members of Moreno Formation (Maastrichtian), Fresno County, California).

[*non*] *Siphogenerita whitei* (Church). Furrer, 1961, Proc. Biol. Soc. Washington, vol. 74, p. 269, Fig. A, figs. 4a-c, 5–7 (Upper Cretaceous, top of cored interval 325–335 feet, Marca No. 3 Well, Panoche quadrangle, Fresno County, California).

[*non*] *Orthokarstenia whitei* (Church). Loeblich and Tappan, 1964, Treatise Invert. Paleo., Pt. C, Protista 2, pp. C567, C568, fig. 446–13a-b (Upper Cretaceous, Maastrichtian, California).

Type Description: "Test elongate, slightly tapering; circular in cross section, widest at apertural end, early stages triserial in microspheric form, biserial in megalospheric form, uniserial in adult. Chambers distinct but only slightly inflated, somewhat overlapping; sutures well marked, slightly indented scalloped lines in upper two-thirds of test, becoming faint dots in initial portion. Megalospheric form sides nearly parallel, initial end rounded and blunt; microspheric form pointed and tapering; wall minutely perforate. Aperture terminal with distinct lip, one side co ex other concave, ending in two inwardly p tooth-like prominences."

Repository of Type Specimen: Holotype collections (no. 7762) of the Department o tology, California Academy of Sciences, S cisco, California.

Stratigraphic Occurrence in California: (lower Ciervian Stage), Upper Cretaceous, to Goudkoff (1945, Tables I and II), but h considered present in zones C′ and D-1 on previous recordings of *S. clarki* var. *costifer* jective synonym of *Orthokarstenia whitei*) i ter biostratigraphic divisions. Zones C, C′, an correlative with the Maastrichtian Stage of t pean Standard of the Cretaceous System (se 1951; Popenoe, Imlay, and Murphy, 1960; and Clark, 1961; Payne, 1962; Colburn, 1 Martin, 1964; among others). Matsumoto (1 Loeblich and Tappan (1964) likewise list a M tian age for the species in California. (Pette pp. 219–222, registers but does not illustrat *generinoides whitei* from [?] Campanian-Maas strata in the Upper Magdalena Province of C and Stone, 1946, p. 473, pl. 72, figs. 8–12, has s to the same species specimens from the " shale" of Peru, which we believe to be of Ca Maastrichtian age. However, we are of the p that the Peruvian fossils should not be referr California taxon. Also, de Klasz (in collabora R. Gageonnet, 1963, p. 294) records but does ure *Siphogenerinoides clarki,* var. *costifera* Coniacian-Campanian Pointe-Clairette beds o Equatorial Africa.

Martin (1964, pp. 41, 42; table 2) show *generinoides whitei* as having a younger stra range ("Zone" C) than *S. clarki* ("Zone" D Moreno Gulch section whereas Payne (1962, 175) states that *S. clarki* often occurs above in surface and well sections along the west si San Joaquin Valley.

Comments: The holotype of *Orthokarsteni* (Church) is without costae, and except for called re-entrant chamber margins, which a lobulate or retroflexed sutures (see Loeblich a pan, 1964), the walls are smooth. Church hims no reference to costae in the description of t type, nor did Martin (1964, pp. 93–94, pl. cially figs. 7–8a-b) in his remarks on topoty mens from the Marca Shale locality. Howeve (1946, p. 473, pl. 72, especially figs. 8a, 10, in an expanded definition of *S. whitei* based pri on hypotype specimens from Peru (comparis topotypes nevertheless was designated) states wall is "highly ornamented by numerous we oped highly irregular short costae, which a continuous and discontinuous over the sut least in the early chambers of the test. Later (1961, figs. 4a and 6) also depicted the spe *Siphogenerita whitei*) with longitudinal costae ations. Conclusions such as these we find incon

e holotype is indeed minus surface ornamen-

nation of faunal assemblages from the type
Orthokarstenia whitei (Church) in Sec. 6,
S.R. 12 E., M. D., discloses that most ortho-
nic specimens encountered therein resemble
errinoides cretacea Cushman (1929, p. 58, pl.
14-15) from the Upper Cretaceous Colon Shale
ebra Honda, Venezuela, in that they possess
tough to varying degrees. Unfortunately, the
f sufficient comparative material makes it diffi-
o determine whether *Siphogenerinoides whitei*
nd *Siphogenerita whitei* of Furrer (= *Ortho-*
i whitei in Loeblich and Tappan, 1964), and
nscribed costate orthokarstenids from the
ounty locality are conspecific with *Ortho-*
i cretacea (Cushman), inasmuch as the orna-
ic of the latter foraminifer varies considerably
in to Stone (1946, p. 472). Or perhaps these
ners may be more closely related to other
e members of the Dietrich genus or even
is one or more new species. Certainly the fossils
t by Stone and by Furrer do not appear to
hkarstenia whitei (Church) following the de-
of the type. Likewise, neither does *Sipho-*
a larki (Cushman and Campbell) var. *costifera*
n and Goudkoff) of Furrer (1961, p. 271,
-and 9) from the Jergins Oil Cheney Ranch
ell in Fresno County resemble the type of
ety or that of *S. whitei* since it, too, bears

uld be recalled that several California micro-
tologists earlier remarked about the close rela-
por similarities of *Siphogenerinoides whitei*
l and *S. cretacea* (Cushman) (see Schenck,
n Hanna in Long, Fuge, and Smith, 1946).

e*Description of Siphogenerinoides clarki var.*
r. "Variety differing from the typical in the
f the test, which, instead of being smooth,
te longitudinal costae.
ne respects this form resembles *Siphogeneri-*
retacea (Cushman) from the Cretaceous of
a, but the general shape of the test and of
bers more closely resemble *S. clarki*."

tory of Type Specimen: Holotype in Cush-
ection (no. 42245) incorporated with U. S.
Museum Collections, Washington 25, D.C.

ents: The well-preserved holotype does not
efinite longitudinal costae as stated in its de-
and no references are made to its re-entrant
margins or retroflexed (lobulate) sutures al-
can be assumed that the latter do not differ
"fairly distinct, very slightly, if at all, de-
sutures of *S. clarki* Cushman and Campbell,
ssibly the retroflexed sutures were regarded
through misinterpretation of the basic mor-
Except for the general configuration of the
fewer chambers, the type of *S. clarki* var.
is so remarkably similar to that of the earlier
Siphogenerinoides whitei Church that we
le to differentiate them. On this basis, the
s considered conspecific with *Orthokarstenia*
whitei (Church), and as such is treated as a subjective synonym. Also, occurrences of the variety outside the type locality are so rare compared with those of *Orthokarstenia whitei* (Church) that one is led to believe identifications are suspect.

Acknowledgments are due Mr. Perfecto M. Mary, School of Earth Sciences, Stanford University, for the camera lucida drawings and the Shell Oil Companies Foundation for a grant-in-aid. Also, we wish to thank Dr. Richard Cifelli, U. S. National Museum, Washington 25, D.C., and Dr. Leo Hertlein, California Academy of Sciences, San Francisco, for loan of type specimens.

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